VISUAL ACUITY WITH LIGHTS OF DIFFERENT COLORS AND INTENSITIES

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I

INTRODUCTION

Although the problems of vision in general, and in particular those of the comparative luminous and physiological effects of the different colors of the visible spectrum, have for many years claimed a large share of the time and thought of investigators in the fields of physics, physiology and psychology, attention has been centered largely upon theoretical considerations. Little effort has been made to give practical application to the principles of color vision which have been established as a result of these investigations, except in so far as they have had reference to esthetics and pictorial art. The artist knows very definitely what combinations of colors should be made in order to produce the effects he desires, but on the other hand the average person of intelligence knows only in the most general way, if at all, what intensities of illumination or what colors of light are best adapted to the purposes of ordinary vision.

This general indifference to the subject of the luminous efficiency of different sources of light has been due largely to the fact that until comparatively recent years the range of intensities and colors available for purposes of artificial illumination has been very much restricted. With the exception of the oxy-hydrogen flame, which is too inconvenient and cumbersome for use outside of the laboratory, the only artificial sources of light available were the incandescent vapors of oils and the ordinary illuminating gas. As both these lights are of approximately similar hue, the question of color differences was never raised, and inasmuch as the intrinsic brightness of each is very low, the only problem involved in their use was that of getting sufficient light from them. Excessive cost and physical limitations precluded the danger of injuriously high intensities of illumination under ordinary conditions.

The last twenty years, however, have brought about a complete revolution in the field of artificial illumination. The utilization of electrical energy for lighting purposes in the various forms in which it is now employed, and the remarkable development of the incandes-

cent mantle for use with gas and oil vapors have made it possible to obtain intensities of illumination scarcely dreamed of before.

Along with the increase in intensity secured by the use of the improved types of lamps have come also wide variations in the hues of the lights in common use. The carbon filament incandescent lamp is the only one of the new types whose color tone approximates that of the old time gas flame. The variations extend from the brilliant white of the Welsbach mantle and the tungsten filament lamp to the strongly colored light of such sources as the mercury vapor arc and the flaming arc, in which certain parts of the spectrum decidedly predominate, and other parts may be entirely lacking.

Further than this, the high intrinsic brightness of these recently developed types makes it possible to vary the hue at pleasure by the use of colored shades, which, notwithstanding their high absorptive indices, nevertheless transmit sufficient light to serve for ordinary purposes.

In view of the great range of variation in intensity and hue which has thus been placed at the disposal of the illuminating engineer, the question of the efficiency of the different types of lamp becomes a very important one. While it is unquestionably desirable to have higher intensities of illumination than those afforded by the gas flame, investigation has shown that increase in intensity is secured only at the cost of a greatly disproportionate expenditure of energy. There must therefore be some point beyond which it would not be expedient, from considerations of economy, to increase the illumination, and this point may best be determined by a study of the actual needs of the eye, with respect to both intensity and hue.

Economical considerations, however, do not afford the strongest argument for adapting the illumination to the needs of the human eye. So large a proportion of the world's work, especially in the large cities, must be done with the aid of artificial illumination, that the welfare of the worker becomes in reality the question of paramount importance. The rapid increase in the number of cases of defective vision has been held to be directly chargeable to the introduction of illuminants of high intensities, and it is, therefore, the first duty of the illuminating engineer to see to it that the eye-sight of those who must work under the light which he provides is properly conserved. In comparison with this consideration, economical efficiency and artistic effect become of secondary importance.

In view of these facts it is obvious that the question of visual acuity under lights of different intensities and of different colors has great practical significance, for it may be assumed as axiomatic that that light is best adapted to the eye which enables it to secure its

maximum efficiency. If it can be shown that there is a point in intensity of illumination below which the eye must work at distinct disadvantage, and beyond which an increase is not attended with a proportionate improvement in acuity, then a strict observance of this limit will be required not only for reasons of economy, but by physiological considerations as well.

Further, it is a matter of common experience that illuminations of certain hues apparently enable the eye to perceive details with greater ease than do illuminations of other hues. Whether this difference is inherent in the color, or whether it arises merely from difference in the intensities of illumination has not been established with any degree of certainty. The assumption has been very generally made and apparently accepted without question that the relation existing between visual acuity and intensity of illumination is a constant one, regardless of the color of the light. In fact, acuity has been made the basis of the judgment of intensity in a number of important physical investigations in light. Thus Lepinay and Nicati[1] determined the luminosity curve for the different portions of the spectrum by means of the acuity test, and the same method was adopted by Langley,[2] A. König,[3] and Pflüger[4] in the determination of the relation between energy and luminosity in different parts of the spectrum. Ferry[5] employed the same principle in his study of the distribution of luminosity in the light of a 16 candle-power incandescent lamp, and in his experiments on the persistence of retinal impressions. There is strong reason to believe, however, that this assumption is not accurate, and that there are specific differences in the effects of lights of different colors upon the eye, apart from those depending upon intensity.

It is the purpose of this investigation, therefore, to make a study of illumination from the point of view of visual efficiency, or adaptation to the needs of the eye, involving not only visual acuity under different degrees of illumination with so-called white light, but also the comparative acuity with lights of different colors.

In reviewing the literature of visual acuity one is struck with the wide variations in the conclusions reached by even the most careful observers. These discrepancies are traceable to two fundamental causes, namely, the failure to standardize the color values and luminous intensities of the sources used, and the lack of uniformity in the objective tests employed in determining the acuity. Discussion

[1] *Annales de Chimie et de Physique*, 5th ser., 24, 30.
[2] *Am. Jour. Sci.*, 1888, 36, 359–380.
[3] *Zeitschr. f. Psych. u. Physiol. d. Sinnesorgane*, 1893, 4, 241.
[4] *Ann. d. Physik*, 1902, 9, 185.
[5] *Am. Jour. Sci.*, 1892, 44, 192.

of the first point will be reserved until later, when the whole question of color photometry will be treated at considerable length.

With respect to the question as to what shall constitute a satisfactory test of visual acuity the greatest variety of opinion is found. In fact, the term visual acuity itself has received several different and entirely inconsistent definitions. Some investigators have understood it to mean the ability to make fine distinctions of light and shade, while others have measured it by the power to distinguish fine details, such as small print, checker board designs, spaces between lines, etc. It is clear that two quite distinct functions of vision, the perception of light and the perception of form, are involved in these different processes, and it is to be expected that results based on the adoption of either definition would diverge greatly from those based on the other.

There is, however, fairly general agreement that the perception of detail affords the most accurate criterion of visual acuity, but even among those who unite on the main proposition there exists great difference of opinion as to the exact form which such tests should take.

Snellen has proposed the use of letters of different sizes which are standardized on the basis of a constant relation between the height of the letters and the distance at which they are to be read. That is, the distance at which any given line of type is to be read is such that it will be viewed under an angle of five minutes of arc. As far as possible, all lines and spaces in a given letter are exactly one fifth the height of the letter itself. With the Snellen test-type the formula for acuity is $V = d/D$, where d represents the actual reading distance for the tested eye, and D represents the prescribed distance at which the line should be read. This form of test-types has met practical requirements more satisfactorily than any other form yet devised, and is in very general use among optometrists.

A new form of acuity test has recently been proposed by Ives,[6] consisting of two gratings such as are used in photo-engraving, superposed upon each other. The principle involved is that if two gratings, consisting of glass plates ruled with fine parallel lines, too close to be separated by the eye (in this case 240 lines to the inch), are laid one over the other and rotated, parallel dark bands are produced, whose separation varies with the angle which the grating lines make with each other.

For this acuity target Ives claims the advantage that the details of the test object are continuously variable in size, while the illumination, the flux of light entering the eye, the distance of the object

[6] *Electrical World*, April 14, 1910, No. 55, p. 939.

and the observer's accommodation remain constant. The screen is illuminated by transmitted light.

In the selection of a satisfactory test of acuity the following requirements should be kept in view:

It should be capable of exact physical measurement, so as to be easily duplicated.

Confusing physiological effects should be eliminated, such as contrast, after-images, irradiation, state of adaptation of the eye.

Psychological sources of error should be guarded against, as suggestion, familiarity, guessing, etc.

The test object should avoid the extremes of both simplicity and complexity. If it is too simple, individual differences or unsuspected sources of error are likely to produce wide deviations in the observations. For example, if the object should consist merely of a straight line of short length, whose direction is to be determined, slight astigmatism in the eyes of the observers would give a constant advantage to certain positions of the line. On the other hand, if the object contain too many or too complex elements, there is the likelihood that the basis of judgment will vary with different observers.

There should be carefully observed the distinction between test objects that are viewed by reflected light, and those that are viewed by transmitted light. In objects that are viewed by transmitted light, there is a high probability that the light sense, as distinguished from the form sense, is playing the more prominent role. In investigations subsequently referred to, it will be found that as a rule those which show a higher acuity for the green end of the spectrum have used transmitted illumination, while those which favor the red have used reflected illumination.

The tests involving the comparative acuity with different colors and intensities should be so arranged that the comparisons need not be made directly. Each test should, if possible, be reduced to an absolute standard. Thus in the work of Dr. Bell subsequently referred to (page 38) the test characters were on two intersecting planes of a wedge, and those illuminated with green light were viewed immediately after those illuminated with white light, and the *degree* of legibility formed the basis of judgment. After the threshold of legibility has been passed, the judgment of degree of legibility becomes a very precarious one.

II

REVIEW OF PREVIOUS WORK IN VISUAL ACUITY

According to Nagel,[1] the first careful study of the relation of acuity to intensity of illumination was made by Tobias Mayer, in the year 1754. His method of observation is not given, but as a result of his investigations he formulated the law that acuity varies as the sixth root of the intensity of illumination.

In 1871, more than a century later, Cohn carried on a series of tests with untrained subjects in ordinary daylight, varying the intensity of the illumination by means of the Weber Polarisation-episkotister. Comparing his own results with those of Mayer, Posch, Albertotti, Sous and Carp, Cohn asserted as his conclusion that "enormous individual differences in visual acuity are found with the decrease in the intensity of illumination, and we are yet far from the formulation of a law for their correlation."[2]

Cohn makes the remarkable statement that he found some eyes that had unit acuity with an illumination of only 1.5 meter-candles, and half acuity with only .6 of a meter-candle. Of all eyes tested, full acuity was attained on the average at 16 meter-candles and half acuity at 4 meter-candles.

Cohn found that it was practically useless to make observations with daylight as the source of illumination, inasmuch as the eye does not by any means show the differences which the photometer shows. That is, within certain limits great variations in the intensity of the illumination are not attended with any noticeable differences in the acuity. Thus for an acuity of 1 the intensity varied to as much as ten times the minimum value; for an acuity of .75 the intensity varied to 12 times the minimum value; and for an acuity of .5 it varied to 7 times the minimum.

Dissatisfied with the enormous variations which he found, Cohn repeated his observations with a great number of persons and took the average of all the readings thus obtained. Assuming unit acuity for 100 units of intensity, an acuity of .75 was obtained with 71 units of intensity, and an acuity of .50 with 33 units of intensity.

In 1876 Posch[3] asserted as the conclusion of a series of observa-

[1] "Handbuch der Physiol. des Menschen," III., 342.
[2] *Archiv für Ophthalmologie*, 1871, 17, (2), 305.
[3] *Archiv für Augenheilkunde*, 1876, 5, (1), 14.

tions that the acuity increases approximately with the logarithm of the intensity; that is, the acuity increases in arithmetical progression as the intensity increases in geometrical progression. The application of this law is subject to the proviso that the intensity be not increased in a ratio greater than that of 1 to 16.

By far the most elaborate and exhaustive investigation of the relation of acuity to intensity of illumination was made by Uhthoff[4] in 1886. Experiments of the same character were repeated by König in 1897.

Uhthoff made his observations at night in a large hall, using as his source of illumination a 4 candle-power petroleum lamp, placed in a suitable box. The light was projected on the chart through a short tube, before which were placed the glass plates and liquids used in producing the variations in color. The intensity was varied in the ratio of 1:3,600,000 by varying the distance of the lamp and by the interposition of smoked glasses, whose coefficients of absorption were photometrically determined. The acuity was judged by ability to perceive the character designed by Snellen, similar in form to the letter E. This figure was cut out of black cardboard and pinned through its center to a background of white cardboard. Before each observation the character was rotated, and the subject, starting from a point too far distant for perception, slowly approached the chart until he was able to tell in which direction the two parallel lines of the figure pointed.

In the earlier course of the investigations red illumination was obtained by passing light through red glass, and blue light by passing it through an absorption cell containing a solution of copper sulphate oxidized with ammonia. This method did not produce satisfactory results, probably because of the great reduction in the luminosity resulting from the use of the color screens, and at the suggestion of König the device was adopted of covering large square tablets of white linden wood with colored fabrics. Red, yellow, green and blue cloths were obtained, which showed practically monochromatic spectra when tested with the spectroscope. The test character was pinned over these fabrics and it was then illuminated by the lamp without the intervention of screens.

Uhthoff tested chiefly persons with good acuity and color-sense, who understood fatigue of the retina, after-images, etc.

For his own eyes, Uhthoff found that unit acuity was attained at about 33 meter-candles. Another observer, *R*, reached it with slightly higher intensity. From this point the curve runs practically parallel with the axis of abscissas.

[4] *Archiv für Ophthalmologie*, 1886, 32, (1), 171.

The following are the values obtained by Uhthoff and another observer:

	Uhthoff					"R"				
Intens.	Wh.	Yel.	Red	Gr.	Bl.	Wh.	Yel.	Red	Gr.	Bl.
3,600	2.03	2.00	1.82	.63	.45	2.00	2.15	2.00	.66	.37
1,175	1.70	1.85	1.44	.61	.39	2.00	2.15	1.74	.56	.32
400	1.52	1.69	1.33	.37	.28	1.80	2.10	1.53	.35	.25
144	1.34	1.54	1.08	.20	.17	1.58	1.68	1.12	.16	.14
36	1.05	1.13	.58	.12	.087	1.14	.92	.61	.09	.077
15	.85	.77	.43	.08	.067	.93	.74	.43	.077	.066
6	.68	.61	.26	.075	.057	.74	.53	.26	.069	.056
1.5	.33	.28	.06	.069	.046	.34	.26	.058	.058	.046
.6	.15	.18	.006	.038	.033	.21	.16	.007	.044	.033
.1	.07	.049		.004	.002	.074	.038		.004	.002
.01	.043	.018				.024	.015			

As a unit of intensity a standard candle was used at a distance of 6 meters. The following curve is plotted from Uhthoff's values, the abscissas representing the intensity in meter-candles, and the ordinates the relative acuity.

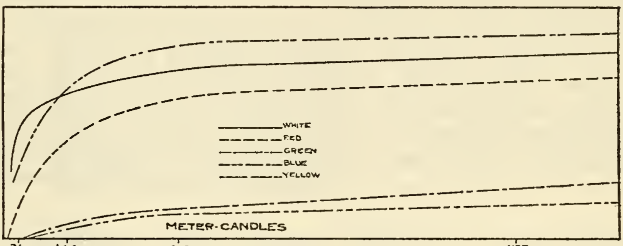


FIG. 1.

As to the relative acuity with the different colors Uhthoff found that above an intensity of about 36 meter-candles yellow gave a higher acuity than white light, but for lower intensities there was no appreciable difference. Red came next in efficiency, falling but little below the white, whereas green and blue gave values far below the other colors, ranging from about 1/3 of the acuity given by white in the higher orders of intensity to 1/10 in the lower orders.

In analyzing the method used and the results obtained in this investigation, the following possible sources of error are pointed out:

1. The character E which was used does not seem to constitute a satisfactory test object. The fact that but a single character was used throughout the observations, allowing the subject soon to become familiar with every detail of this figure, makes it possible and indeed highly probable that in many instances good guessing was

substituted for clear perception. In order to determine this point experimentally a test was made by the writer with several unexperienced observers, using Landolt's ring-form test figure, about 5 mm. in diameter with an opening of about 1 mm. The subjects were asked to indicate the fact as soon as they had approached near enough to the chart to make a good guess as to the angle in which the opening was located. They were then asked to approach until they were quite certain as to the position of the opening. It was found that in a large proportion of cases correct guesses could be made when the observers were at distances two and even three times as far as was required for clear perception. Very often the first glance would give a clue to the location of the opening, whereas prolonged gazing at the same distance would result in utter uncertainty. It is true, of course, that the practised observer may check this tendency toward guessing by setting for himself a standard of clarity of perception to be attained in each observation, but none the less the wide limit of uncertainty seems to introduce an excessive amount of inference into the method.

2. To put the black character on the colored background and then to view it with white light must necessarily produce an entirely different effect from that which would be produced by illuminating a white background containing the superimposed character with the corresponding color of light. The contrast between the black character and the blue or red fabric is much less than that between the character and the white background illuminated with blue or red light.

3. Further, it is very much to be questioned whether the photometric method used to determine the intensity of the colored lights was sufficiently accurate to insure the elimination of serious error. Many observers claim an even greater acuity for the green-blue end of the spectrum than for the red end, and my own results would tend to show that the difference is not nearly so great as Uhthoff finds to exist.

Asserting that the investigations of Uhthoff had been unsatisfactory in their results for the reason that the intensities of illumination had not been varied within sufficiently wide limits, and for the additional reason that the observations had been too few to eliminate the errors necessarily associated with the work, König[5] repeated the experiments in 1897 in a somewhat modified form. He used the same test character, the Snellen E, and adopted the same method of securing variations in color, except that he passed his light

[5] *Sitzungsbe. d. Berliner Akad. d. Wiss.*, 1897, 13, 559.

through glass of the same color as that which formed the background of his test character. The intensity was varied by changing the distance of the source and by using different sources—the candle, large and small petroleum lamps, the Auer light and the electric arc. With white light the lower intensities were obtained by the interposition of ground glass screens. The standard unit of intensity was the Hefner lamp at 1 meter's distance.

Unit acuity was taken as the acuity necessary to determine with approximate certainty the position of the opening in the figure when it was viewed under an angle of five minutes. The determinations were made in three different ways:

1. The intensity of illumination was fixed, and the readings were made by the observers both receding and approaching.

2. The value of the acuity was fixed by placing the subject at a given distance, and the intensity necessary for perception at this distance was determined both by increasing and decreasing the illumination.

3. The distance of the observer and of the light were varied simultaneously until the desired clearness of perception was secured.

König states that in these observations one must be satisfied with only approximate certainty, but must be careful at the same time to maintain the same standard throughout the observations. If one demands too high a degree of certainty the eye will become fatigued within fifteen minutes, whereas if one is satisfied with less accuracy, the observations may be continued for hours without making any appreciable difference in the readings.

White		*Red*		*Green*		*Blue*	
Intens.	Acuity	Intens.	Acuity	Intens.	Acuity	Intens.	Acuity
.12	.18	.24	.07	.15	.05	.22	.02
.24	.269	.50	.10	1.00	.09	1.44	.04
.50	.46	1.15	.23	4.00	.10	2.04	.05
1.00	.596	4.94	.41	11	.11	6.02	.06
3.95	.769	8.17	.51	52	.19	26.3	.10
9.97	1.11	10	.55	112	.27	29	.08
12.88	.86	20	.67	208	.62	100	.11
20.6	1.10	44.4	.82	515	.516	260	.15
26	1.09	64	.89	2,269	1.00	629,800	.64
51	1.43	82	.87	130,200	1.63		
54.5	1.16	82	.87	130,200	1.63		
51	1.43		.92				
54.5	1.16	82	.92				
80	1.31	100	1.08				
123	1.43	205	1.11				
168	1.47	7,900	1.81				
264	1.56	40,820	1.74				

König gives the above results for his own eyes. No attempt is made to reduce the intensities for different colors to the same basis.

From these observations König deduced the following formula to express the relation between acuity of vision and the intensity of illumination:

$$S = a(\log B - \log C)$$

S denotes the visual acuity and B the intensity of illumination. The factor a is not explained, but the statement is made that it is independent of the nature of the lamp. C is a constant inversely proportional to the brightness value of the lamp used. a and C may be essentially different, according as rods or cones serve to receive the light stimulus. In the first case a may be ten times as great as in the second case.

Basing his opinion on the fact that in the low orders of illumination the acuity rises slowly with the intensity and more rapidly in the higher orders, König conjectured that in acuity two different sorts of elements of the sensitive layer in the retina are involved, namely, the rods and the cones. With the lower intensities the rods are active, and as the intensity increases they are relieved by the cones even before they reach the upper limits of their capacity. These cones likewise increase in their power until they also finally reach their limit.

König states that as a matter of fact in the determinations which belong to the slowly ascending portion of the acuity curve, fixation was not made with the fovea, but somewhat eccentrically; with the increasing intensity of illumination, corresponding to the more rapidly ascending portion of the acuity curve, fixation is made with the fovea. With a totally color-blind eye which König tested, the whole course of the curve corresponded to the slowly-ascending portion of the curve of the color-perceiving eye, and he concluded from this fact that the incapacity of the cones of such an eye is also the cause of the low acuity constantly associated with this anomaly.

With respect to the relative acuity for lights of different colors König is inclined to agree with Helmholtz in the opinion that we can, independently of color, see equally well with equal intensities of illumination.

This conclusion is controverted by Örum,[6] who studied the comparative acuity with different colors by means of groups of illuminated points on a black background. The distance at which these

[6] *Skandinavisches Archiv für Physiol.*, 1904, **16**.

points could be individually perceived was taken as the measure of acuity. Örum found that the acuity for white illumination was greater than for any one of the three fundamental colors assumed by the Young-Helmholtz theory of color vision, and that the relative acuity for the colors red, green and blue stood in the ratio of 3:2.5:2, in the order named.

At the suggestion of Nagel, who considers the work of both König and Örum as open to criticism on certain points, the problem has recently been studied by A. Boltunow.[7] Determinations of intensity were made with a Schmidt and Haensch flicker photometer. Snellen's Haken was first used as a test object, but later this was replaced with the ring-form character of Landolt. This figure was cut out of a metal plate and fixed before a square of colored glass, which was illuminated from behind by a source of light enclosed in a box. The observer thus looked directly toward the source of light, seeing only the light transmitted through the outline of the figure. The ring was rotated before each observation, and its opening was made to lie in one of four positions, above, below, or to the right or left side.

The observer indicated the position of the opening ten times for each distance chosen, and when he was correct eight times out of the ten, this distance was accepted as the proper one.

Only one degree of intensity was used, and this was not described in standard units. It was only known that the illuminations given by the different lights were of the same intensity, as determined by photometric comparison. At first a very high intensity was used, so that the optimum acuity was exceeded. The illumination was consequently reduced one half by means of an episkotister, when it was found that actual increase of acuity resulted. This fact in itself indicates that there was some serious defect in the method. It is conceivable that a further reduction of intensity might have resulted in still higher acuity, and we should thus have the acuity varying inversely as the intensity, which is of course contrary to all normal experience.

Boltunow concludes from his observations that white light affords the highest acuity, with green next in order, and that red is the least efficient. So far as high intensities are concerned, he attributes the difference between red and green to various physical factors, as aberration, irradiation, etc.

As was pointed out in the case of König's work, the test character employed in this investigation does not seem well adapted to securing

[7] "Über die Sehschärfe im farbigen Licht," *Zeitschrift f. Psych. u. Physiol. d. Sinnesorgane*, 1907–8, 42, (2), 359.

accurate measures of acuity. The wide range of values secured by the same observer gives evidence of this. For the red illumination the distance representing the measure of acuity ranged from 430 cm. to 520 cm., and for the green it ranged from 510 cm. to 610 cm.

The last recent study of visual acuity as related to illumination of different colors to which reference will here be made was undertaken by Messrs. Broca and Laporte[8] in Paris in 1908. They employed sources of light in ordinary commercial use, the carbon filament incandescent lamp, the ordinary carbon arc lamp, and the mercury vapor arc. The effects of these lights upon the eye were studied with respect to acuity, speed of reading, and fatigue.

Figure 2 represents a diagram of the apparatus which was used for determining the intensity of illumination, and for making the various tests with the eye.

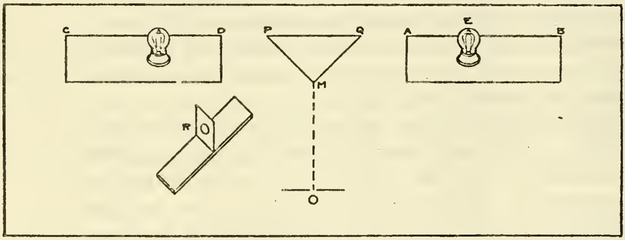


FIG. 2.

A Ritchie wedge, 45 degrees, *PMQ* in the figure, is placed at one end of a photometric bench, *AB*, so that the plane which bisects the angle *PMQ* of the prism is perpendicular to the axis of the bench. On the surface of the prism *PM* was placed a Parinaud's optometric chart, which was illuminated by the source of light under observation. The opposite plane of the prism carried a piece of paper of the same whiteness as the chart, but without printing. This plane was illuminated by a standard lamp on the photometric bench. In the bisecting plane of the prism, at *O*, was a screen at which the observer placed his eye in order to determine the relative intensity of illumination of the two surfaces of the prism. This determination was made by the ordinary direct method, the two surfaces being assumed to be equally illuminated when they seemed to be so to the observer. It is admitted by the authors that this photometer lacks sensitiveness, and that different observers obtained systematic differences in

[8] *Bulletin de la Société Internationale des Electriciens*, Paris, 1908, 2d series, No. 76.

their determinations. Each observer made his acuity tests on the basis of his own photometric values. In view of the great difficulty involved in making direct comparison of colored lights pointed out elsewhere, it would seem that this failure to determine with greater exactness the relative intensities of the different lights would greatly impair the value of these observations.

Perpendicular to the plane of the optometric chart was a bench carrying a screen *R*, with an aperture of 2 mm. in diameter, through which the chart was read in order to determine the acuity. This screen served the double purpose of fixing the position of the eye at its maximum reading distance, and of eliminating variations due to changes in the size of the pupil. Inasmuch as the diameter of the pupil would vary under these illuminations from 4 to possibly 7 mm., this arrangement would result in cutting down the area of the pupil exposed to the lower intensities to a value of only one fourth to one twelfth of its actual size. Certainly this would produce a great deviation from actual reading conditions, and the authors state that the acuity was in fact considerably diminished by this screen for low illuminations.

The conclusion is drawn from these observations that "all ordinary sources of light, when they give to a paper the same degree of luminosity, give to the observer at the same time the same visual acuity and speed of reading. It is almost certain in such cases that the retinal fatigue is the same, and that the contraction of the pupil is also the same."

III

PRELIMINARY STUDY

The preliminary observations here reported were made not so much with the hope of securing accurate results as with the purpose of becoming familiar by actual trial with the important details of procedure, in order that sources of error might be discovered and, as far as possible, eliminated before taking up the more exact study of the problem.

In making choice of the various tests proposed for the study of visual acuity, the writer was governed largely by the consideration that the chief function which the eye is called upon to perform under artificial illumination is that of reading. Characters of the alphabet were therefore chosen. Even though such a test-object may be open to theoretical objections, its use would seem to yield results of the highest degree of practical application, in view of the very general use of such characters among optometrists.

The apparatus and method of procedure were as follows: At one end of a long bench conveniently graduated was placed a stand supporting a Snellen's optometric chart. On this chart the line of type was selected which should be read by the normal eye under average daylight illumination at a distance of three meters. This line was chosen for the reason that it happened to be the most convenient for the distances and intensities of illumination available. It was the intention at first to use all the letters in the line for observation, but a few trials developed the fact that the letters varied considerably in legibility, and full perception of the line therefore resolved itself into perception of the least legible letter in the line. This letter was found to be *R*, and consequently the attention was centered upon it, the effort being made to perceive it at each observation with the same degree of distinctness.

For the illumination of the chart the following sources of light were used:

Ordinary carbon filament lamps, with clear glass bulbs, with nominal ratings of 2 and 16 candle power respectively;

Carbon filament incandescent lamp, with ruby bulb, nominally rated at 16 candle power, but with an actual intensity, as subsequently determined photometrically, of .6 candle power;

Carbon filament incandescent lamp, with blue bulb, rated at 16 candle power, with an actual intensity of 1.1 candle power;

Carbon filament incandescent lamp, with green bulb, rated at 16 candle power, with an actual intensity of 1.6 candle power.

Spectroscopic tests of these colored bulbs showed that the red lamp yielded practically monochromatic light, while the green and blue bulbs transmitted light of all wave-lengths.

In order to get higher intensities in the red light, a second and larger lamp of the same type was used. Although its nominal rating was twice that of the smaller lamp, it was necessary to operate it at a much lower voltage, so that it yielded a calculated candle power of only .76. Readings with this lamp were overlapped with those of the smaller one, and the values were found to be approximately identical. These lamps were all supplied with current from a storage battery circuit, and care was taken that the voltage remain constant during the observations.

The method of determining the candle power of the colored lamps will be fully discussed in a later section.

The intensity of illumination with any given lamp was varied by varying its distance from the chart, the intensity being calculated by the law of inverse squares. The illuminating lamp was placed in a small wooden box, so arranged that its light could fall upon the chart, but could not in any way directly affect the eye of the observer. The walls, floor, ceiling and furnishings of the room in which the experiments were conducted were painted black, so that the effect of diffused light may be regarded as negligible. Sufficient time was always allowed for adaptation in going from daylight into the darkroom.

The illumination of the chart having been suitably arranged, the observer would recede to a point at which the letters were entirely illegible, and then gradually approach the chart, stopping at the point at which he secured the desired clearness of perception of the test-character. This distance was carefully measured with a flexible metric scale, which extended from the chart to the eye of the observer. Each observation was repeated at least five times, and the average of all the readings was then calculated. The greatest deviation from the average distance was usually within 5 per cent. of the total distance, although it was found difficult to decide for one's self, under all conditions, what degree of legibility was required. Thus for high intensities of illumination one would feel that he was instinctively demanding a clearer perception than when the intensity was low. Efforts were of course made to reduce such effects to a minimum.

After determining the average reading distance for any given illumination, the visual acuity was calculated by dividing the found

Acuity Readings

TABLE I

With 2 cp. Carbon Filament Lamp

Intensity in Meter-candles	Acuity	Reading Dist. in cm. Av.	Range
.125	.29	88	85– 92
.25	.40	120	110–130
.50	.49	148	134–162
1	.57	171	160–182
2	.69	206	200–210
4	.77	231	225–240
8	.85	255	245–265
12	.89	269	260–275
16	.95	285	270–295
20	.97	291	290–295
24	1.00	301	295–305
28	1.02	305	300–310
32	1.04	313	310–325
Supplementary with 16 cp. lamp			
4	.76	228	227–230
8	.85	256	252–260
16	.94	281	270–288
32	1.02	305	300–310
64	1.05	316	313–320
128	1.07	322	318–325
256	1.10	330	325–332

TABLE II

With Red Bulb

Intensity in Meter-candles	Acuity	Reading Dist. in cm. Av.	Range
.03	.05	15	15– 16
.036	.12	36	35– 37
.05	.15	46	44– 48
.06	.19	58	55– 58
.10	.22	67	64– 70
.15	.31	92	90– 94
.26	.36	109	107–110
.60	.47	140	138–145
1.22	.63	191	188–195
1.67	.64	193	188–200
2.40	.68	205	195–212
2.96	.73	218	215–225
3.74	.74	223	215–230
4.90	.79	238	228–248
6.67	.82	245	242–248
9.60	.87	260	250–265
15.00	.92	275	270–280
Supplementary with .767 cp. lamp			
12	.91	274	270–280
16	.96	289	280–295
20	1.01	303	300–310

TABLE III

With Green Bulb

Intensity in Meter-candles	Acuity	Reading Dist. in cm. Av.	Range
.08	.20	62	60– 65
.10	.23	70	70– 70
.13	.26	79	75– 82
.18	.31	94	90–100
.26	.35	105	100–108
.40	.42	127	125–130
.71	.49	148	145–150
1.60	.63	190	187–192
3.26	.69	207	204–210
4.44	.72	215	210–220
6.40	.75	224	220–230
7.90	.82	245	240–250
13.06	.87	260	250–275
17.77	.91	274	270–280
25.60	.95	285	280–290
40	1.04	312	300–320

TABLE IV

With Blue Bulb

Intensity in Meter-candles	Acuity	Reading Dist. in cm. Av.	Range
.05	.11	34	33– 34
.06	.15	44	40– 47
.08	.20	60	58– 62
.11	.22	67	65– 69
.18	.26	77	77– 77
.26	.30	90	87– 92
.48	.36	108	105–110
1.10	.52	155	150–160
2.25	.60	182	175–188
3.05	.64	192	188–198
4.40	.69	207	200–210
5.10	.72	216	212–220
6.90	.74	223	218–226
8.98	.80	241	235–245
12.21	.87	262	258–265
17.60	.88	264	260–270
27.50	.92	275	270–280

distance in centimeters by 300, the standard distance of the line. Thus an illumination which allowed the line to be clearly perceived at 150 centimeters was said to give an acuity of .5.

The writer determined by test that his own eyes, aided by spectacles, possessed practically unit acuity under average daylight illumination.

Tables I, II, III and IV give the results of these observations.

Table V. gives a summary of the acuity values obtained with the lights of different colors, arranged with a view to easy comparison:

TABLE V

ACUITY AND INTENSITY.—SUMMARY

Intens. in M.-c.	Wh.	Red	Gr.	Bl.	Intens. in M.-c.	Wh.	Red	Gr.	Bl.
.03		.05			4.00	.76 .77			
.036		.12			4.40				.69
.05		.15		.11	4.44			.72	
.06		.19		.15	4.90		.79		
.08			.20	.20	5.10				.72
.10		.22	.23		6.40			.75	
.11				.22	6.67		.82		
.125	.29				6.90				.74
.13			.26		7.90			.82	
.15		.31			8.00	.85 .85			
.18			.31	.26	8.98				.80
.25	.40				9.60		.87		
.26		.36	.35	.30	12.00	.89	.91		
.40			.42		12.21				.87
.48				.36	13.06			.87	
.50	.49				15.00		.92		
.60		.47			16.00	.95 .94	.96		
.71			.49		17.60				.88
1.00	.57				17.77			.91	
1.10				.52	20.00	.97	1.01		
1.22		.63			24.00	1.00			
1.60			.63		25.60			.95	
1.67		.64			27.50				.92
2.00	.69				28.00	1.02			
2.25				.60	32.00	1.04 1.02			
2.40		.68			40.00			1.04	
2.96		.73			64.00	1.05			
3.05				.64	128.00	1.07			
3.26			.69		256.00	1.10			
3.74		.74							

While it would be unsafe to attempt to draw any definite conclusions from these preliminary observations, the following points may be indicated as being brought out with considerable clearness:

1. The increase of acuity with intensity is very much more rapid in the lower orders of illumination.

¼ acuity is obtained with about	.10	meter-candle intensity;
½ acuity is obtained with about	.60	meter-candle intensity;
¾ acuity is obtained with about	4.00	meter-candles intensity;
unit acuity is obtained with about	24.00	meter-candles intensity;
1.10 acuity is obtained with about	256.00	meter-candles intensity.

2. The curve of acuity (Fig. 3) which is plotted from the figures given, using the measures of intensity in meter-candles as abscissas and the measures of acuity as ordinates, is seen already to have turned from a vertical toward a horizontal direction at about 2 meter-candles intensity; after unit acuity is reached the curve becomes approximately parallel to the axis of abscissas.

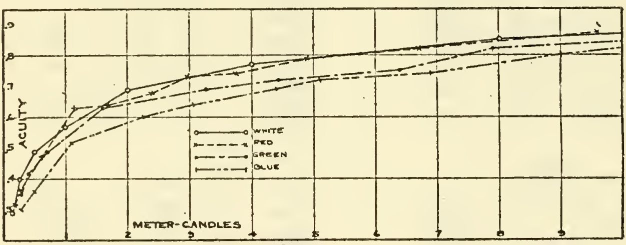


FIG. 3.

3. As to the effect of different colors upon acuity, while the writer does not find nearly so great a decrease in efficiency for the green and blue lights as Uhthoff found, it is quite clear that whatever differences may exist are in favor of the colors at the red end of the spectrum.

This difference between the detail-revealing power of red light and that of blue or green light is strikingly brought out by ordinary direct observation in the dark room. Under illumination with the red lamp the walls and tables, which were painted black, at some distance from the lamp were shrouded in gloom, while with the green light the walls and other objects were quite conspicuous. When, however, the test chart was exposed, the black characters stood out clearly defined against the white background under the red illumination, whereas with the green light the characters were scarcely perceptible. This difference is apparently due to the fact that the black

absorbs practically all the red rays which fall upon it, whereas a large proportion of the green light is reflected by it.

Improvements in Method

In the course of these preliminary observations several possible sources of considerable error were discovered. The first of these has already been alluded to, and consists in the large element of guessing which is involved in observations with a test-character which is, or may soon become, perfectly familiar. In order to eliminate this element as far as possible and yet retain a test of the same general character, for the Snellen's chart was substituted a series of letters of heavy faced Gothic type of approximately the size of the Snellen 3-meter line. The following line shows the exact size and style of the type used:

A B C D E F G H

Those letters of the alphabet were discarded which seemed especially legible, as the I and L. Several numerals were used also. Most of the characters were used three times, giving a total of about 80 characters in the whole series. These were arranged along the circumference of a cardboard disc about 8 inches in diameter in such order as to avoid the recurrence of similar combinations of letters. This disc was mounted vertically on an axis, and was covered with a plate having near its upper side a slot through which a series of six characters could be exposed at one time. The disc was rotated for each observation, and the observer was required to approach the disc until five of the six letters could be read correctly to the assistant.

A second source of error was associated with the generally recognized difficulty involved in making photometric measurements of the intensity of lights of different colors, and at low orders of illumination. In the preliminary experiments it was necessary to carry the lamps used to the physics laboratory in order to determine their intensity photometrically. This laboratory had white walls and a considerable amount of diffused illumination which could not be eliminated. This defect, along with the difficulties involved in exactly duplicating the voltages of the lamps in the dark room and in the laboratory, introduced a considerable amount of uncertainty into the determinations of the candle power of the lamps. It was therefore found advisable to set up a photometer in the dark room, and make the acuity observations at the same time that the lamps were photometered.

The plan adopted was as follows: A 2-candle-power carbon filament incandescent lamp, with constant voltage, was set up on the right-hand side of the photometer head at a fixed distance, and the lamp which was intended to be used for the acuity tests was brought to balance on the other side. This lamp was then set at the same distance from the disc with the test-characters, and the acuity observations were made.

The 2-cp. lamp was then set at another fixed distance and the process repeated. In this manner not only the colored lamps but also a carbon filament 4-cp. lamp and a photometric standard lamp were balanced against the 2-cp. lamp, and thus conditions of illumination were duplicated for each lamp, and the absolute intensities of the lamps at the given voltage were determined as well.

The following tables give the results of these observations. The 2-cp. lamp was maintained at 112 volts, and the red, green and blue lamps at 108 volts. The standard lamp was rated at 16 candle power at 106.1 volts, and the 4-cp. lamp used in the observations was maintained at 112 volts.

TABLE VI

Dist. of 2-cp.	*Distance in Cm. to Balance of*				
Lamp in cm.	Red	Green	Blue	4-cp.	Stand.
500	*268	*434	*359		
400	*214	*347	*282		
300	*160	*260	211	*447	
250	*133	*217	176	*372	
200	*107	*173	141	*298	*550
150	*80	129	107	*223	*411
100	53.6	86.5	71.8	149	278
75	40	65.5	54	112	205.8
50	26.5	44.2	*36	74.5	137.5

* Distances marked with asterisk are estimated on basis of readings taken at 150, 100, and 75 cm., as these are more accurate, because of higher intensity.

Determination of Candle Power

The values given in Table VI. were used to determine the absolute candle power of the red, green and blue bulbs used in the preliminary experiments, for the reason that they were secured under improved photometric conditions, and may therefore be presumed to be more exact than the earlier determination made in the physical laboratory.

All readings taken at different distances of the 2-cp. lamp are in Table VII reduced to their equivalents at 100 cm. That is, readings at 50 cm. are doubled, those at 75 cm. are increased by one third, etc. A rough average is then made of these different readings,

weight being given to those values which were actually made at 100 cm. and 75 cm., rather than to the reduced values.

TABLE VII

Dist. of 2-cp. Lamp in Cm.	Red Actual Reading in Cm.	Red Reduced	Green Actual Reading	Green Reduced	Blue Actual Reading	Blue Reduced	Standard Actual Reading	Standard Reduced
300					211	70.3		
250					176.5	70.6		
200					141	70.5		
150			128.8	85.9	107	71.3		
100	53.6	*53.6*	86.5	*86.5*	71.8	*71.8*	278	*278*
75	40	53.3	65.5	87.3	54	72	206	275
50	26.5	53	44.2	88.4			137.5	275
Average		*53.5*		*87*		*71.5*		*276*

The candle power of the red, green and blue lamps will have the same ratios to the standard 16 cp. as the squares of their respective distances. Thus the candle power of the red is $53.5^2/276^2 \times 16$ cp. or .60 cp.; the candle power of the green lamp is $87^2/276^2 \times 16$ cp. or 1.6 cp.; the candle power of the green lamp is $71.5^2/276^2 \times 16$ cp. or 1.1 cp.

The acuity readings made under these modified conditions are given in Table VIII. Table IX. gives the results with distances of the lamps reduced to intensity in meter-candles and the reading distances reduced to acuity, the latter value being obtained by dividing the distances by 272 cm. This divisor represents the average of 21 readings of the chart under average daylight illumination, with an average deviation of 7 cm. These readings were as follows: 258, 259, 260, 262, 264, 264, 266, 268, 270, 271, 274, 275, 275, 276, 276, 277, 280, 281, 283, 283, 288.

TABLE VIII

READING DISTANCES WITH RED, GREEN, BLUE STANDARD AND 4-CP. LAMPS, WHEN BALANCED AGAINST 2-CP. LAMP AT FIXED DISTANCES

2-cp. Lamp, Cm.	Red, Cm.	A. D., Cm.	Green, Cm.	A. D., Cm.	Blue, Cm.	A. D., Cm.	Stand., Cm.	A. D., Cm.	4-cp. Cm.	A. D., Cm.
500	50	3	47	1						
400	62	1.5	62	1.5						
300	89	4	75	2	80	2			91	2
250	100	4	87	2	92	3			112	3
200	119	4	100	4	104	2	122	3	120	4.7
150	141	2.8	117	2	113	3	143	4	145	3
100	174	4	151	2.4	137	5	170	3	161	2
75	195	4	181	4	161	3	195	1.5	189	4.6
50	224	3	208	4	181	3	219	5	218	2.5

TABLE IX

Distance of 2-cp Lamp. Cm.	Intensity in Meter-candles	*Acuity for* Red	Green	Blue	Standard	4-cp.
500	.085	.183				
400	.133	.228	.228			
300	.236	.327	.275	.294		.334
250	.340	.367	.319	.338		.411
200	.531	.437	.367	.382	.448	.440
150	.944	.517	.429	.415	.525	.532
100	2.125	.639	.554	.503	.624	.591
75	3.778	.716	.664	.591	.716	.694
50	8.500	.822	.763	.664	.804	.800

Continued with standard lamp:

5.33	.752
12.00	.936
21.33	1.035
48.00	1.127
85.33	1.185
192.00	1.270

The curves (Fig. 4) which are plotted from these values show the same general characteristics as those obtained from the preliminary observations. The red and the white illuminations yield approximately equal acuity, while both are considerably higher than the green. The acuity with the blue illumination is the lowest.

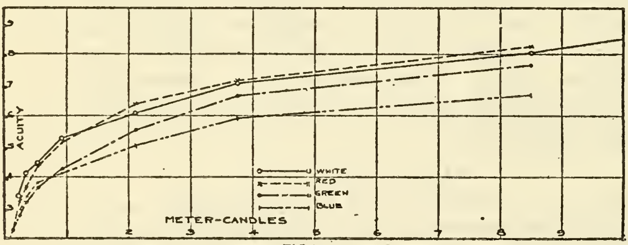


FIG.4.

IV

MAIN OBSERVATIONS IN ACUITY

Attention has already been called to the fact that of the colored incandescent bulbs used in the preceding observations only the red gave approximately monochromatic light, and this was of very low intensity. In order to increase the intensity of the red illumination and to secure more nearly pure colors in the green and the blue, it was found necessary to adopt a different source of light.

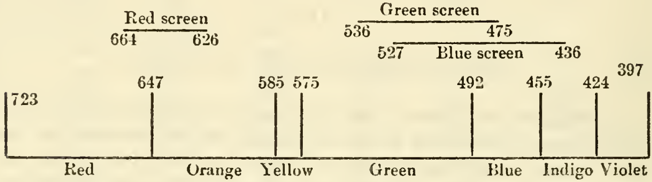
An attempt was made to project a spectrum by means of a collimating lens and prism, following the arrangement used by Abney in his work on color vision. This method, however, was found impracticable, for the reason that it was impossible to secure a sufficiently large field of uniform intensity and color tone to meet the requirements of this study.

Several other devices were tried, as combinations of colored glasses and gelatines, but none of these yielding satisfactory results, recourse was finally had to colored liquids contained in absorption cells. For red a dye was used called poncean red, a strong solution of which transmitted a color well within the limits of the red, ranging from 664 $\mu\mu$ to 626 $\mu\mu$. The red incandescent bulb and a glass plate which was subsequently used yielded light within practically the same limits of wave-length.

In order to secure a satisfactory green it was necessary to use two solutions—a saturated solution of copper chloride and a weak solution of crystal violet. This yielded an illumination in which green strongly predominated, without any yellow but with a touch of blue. The wave-length ranged from 536 $\mu\mu$ to 475 $\mu\mu$, but the blue was of so low intensity that its effect may be considered negligible.

It was found to be entirely impossible to produce a pure blue of sufficient intensity to be accurately photometered or to be used in acuity tests. A solution of copper sulphate oxidized with an excess of ammonia gave a practically pure blue, if left of full strength, but as has already been said, the intensity of the light thus transmitted was too low to be available. It was necessary therefore to dilute the solution with water, and this extended the spectrum a considerable distance into the green, the wave-length ranging from 527 $\mu\mu$ to 436 $\mu\mu$. To the direct vision, however, the illumination was distinctly blue, there being no suggestion of the green component.

The extent of the spectrum covered by the different colors is represented in the following diagram, based on Listing's scale:



As the source of light a Nernst glower was used, of 68.25 candle power, enclosed in a cubical box of about 12 inches on a side. The light was emitted through an aperture in one side of the box, about three inches in diameter, before which the cells containing the liquids were placed.

In this series of observations three persons in addition to the writer acted as observers. For each the acuity in daylight vision was determined by twenty readings of the chart, and this value was used as a basis in determining the acuity with the colored lights. The observers were cautioned not to attempt to beat previous records in successive trials, but rather to adopt a fixed standard of legibility and to adhere to it as closely as possible in each observation.

It was found that it was not always possible to keep exactly the same angle between the line of sight of the observer and the direction of the light incident upon the chart, and this change of angle was likely to be accompanied by more or less glare. Wide variations in any series of readings may find a partial explanation in this fact.

Observers would occasionally find difficulty in the clearing up of the characters, dependent not upon the intensity of illumination, but rather upon the defective focusing of the eye.

The following tables give the results for the different observers:

TABLE X

OBSERVER BR.

White		*Red*		*Green*		*Blue*	
Intensity in M-c.	Acuity	Intensity	Acuity	Intensity	Acuity	Intensity	Acuity
.96	.47	.62	.43	.11	.18	.10	.16
1.28	.52	.97	.48	.16	.21	.18	.18
1.91	.61	1.72	.52	.29	.25	.41	.21
3.51	.66	3.90	.55	.66	.33	.73	.25
5.10	.69	6.90	.58	1.17	.39	1.64	.33
7.97	.72	15.60	.73	2.65	.43	2.56	.37
		24.37	.75	5.40	.49		

TABLE XI

OBSERVER H.

White Intensity in M-c.	Acuity	Red Intensity	Red Acuity	Green Intensity	Green Acuity	Blue Intensity	Blue Acuity
1.24	.46	.09	.21	.02	.08	.02	.10
1.79	.56	.12	.26	.05	.12	.05	.14
2.79	.63	.19	.30	.12	.19	.12	.19
4.95	.74	.33	.38	.21	.25	.20	.26
11.17	.73	.75	.46	.48	.34	.46	.32
19.81	.76	1.33	.50	.85	.42	.82	.40
44.70	.83	3.00	.53	1.92	.48	1.84	.46
178.80	.92	12.00	.61	3.91	.57	3.75	.54
		24.00	.68				

TABLE XII

OBSERVER BE.

White Intensity in M-c.	Acuity	Red Intensity	Red Acuity	Green Intensity	Green Acuity	Blue Intensity	Blue Acuity
1.00	.49	.125	.25	.125	.14	.125	.13
2.00	.60	.25	.40	.25	.21	.25	.19
4.00	.68	.50	.55	.50	.27	.50	.24
8.00	.77	1.00	.60	1.00	.34	1.00	.32
16.00	.84	2.00	.71	2.00	.40	2.00	.38
32.00	.91	4.00	.75	4.00	.48	4.00	.43
64.00	.95	9.40	.82	8.00	.56	8.00	.48
		16.00	.89	16.00	.59		

TABLE XIII

OBSERVER RI.

Red Intensity	Red Acuity	Green Intensity	Green Acuity	Blue Intensity	Blue Acuity
.125	.25	.11	.18	.10	.17
		.16	.21	.18	.22
.25	.36	.29	.25	.41	.30
		.66	.36	.73	.39
.50	.48	1.17	.41	1.64	.49
		2.65	.52	2.56	.53
1.00	.56	5.40	.59		
2.00	.61				
4.00	.72				
8.00	.79				
9.40	.81				
16.00	.86				

The accompanying curves (Figs. 5, 6, 7, 8) represent the values obtained by the individual observers in graphic form. In Fig. 8 the lower of the two curves for red represents a series of values not given in the tables.

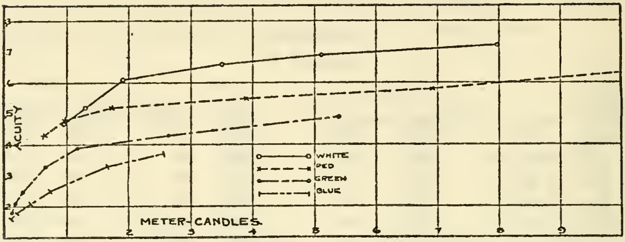


FIG.5.

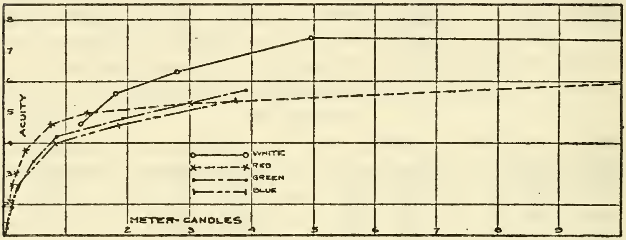


FIG.6.

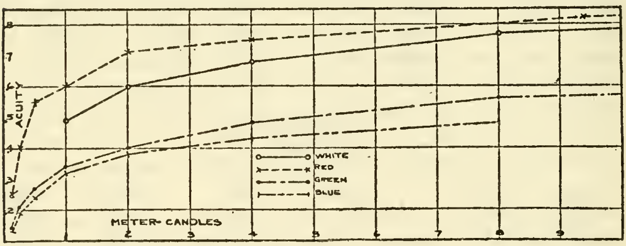


FIG.7.

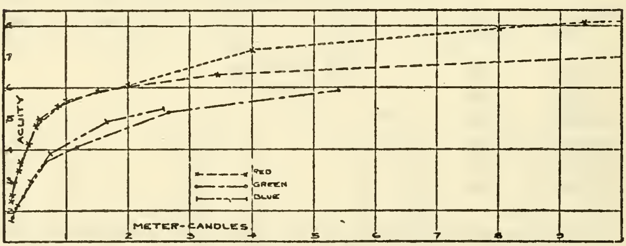


FIG.8.

In order to compare the results of each individual for the different colors and as well to secure the averages for the different observers it is convenient to reduce the values to the same series of abscissas. This was done by taking the values of the ordinates for fixed points along the axis of abscissas.

Table XIV. gives the acuity values of each observer for the various colors and for white.

TABLE XIV

INTENSITIES IN METER-CANDLES

	.125	.25	.50	1.	2.	3.	4.	5.	8.	10.
Ri.										
White	.29	.36	.44	.53	.60	.65	.71	.73	.79	.86
Red	.25	.36	.48	.56	.61	.67	.72	.74	.79	.81
Green	.19	.23	.31	.40	.48	.53	.55	.58		
Blue	.18	.23	.32	.42	.50	.54				
Br.										
White				.47	.62	.65	.67	.69	.72	
Red				.49	.52	.54	.56	.57	.60	.63
Green	.19	.24	.30	.37	.41	.44	.46	.48		
Blue	.17	.19	.22	.28	.34					
H.										
White					.58	.64	.69	.74	.74	.74
Red	.26	.34	.42	.48	.51	.53	.54	.55	.58	.59
Green	.19	.26	.34	.43	.49	.53	.58			
Blue	.19	.27	.32	.41	.47	.51	.55			
Be.										
White				.49	.60	.64	.68	.70	.77	.78
Red	.25	.40	.55	.60	.71	.73	.75	.76	.80	.82
Green	.14	.21	.27	.34	.40	.44	.48	.50	.56	.57
Blue	.13	.19	.24	.32	.38	.41	.43	.44	.48	

With the exception of the case of the writer, in which the values for the blue lie slightly above those for the green, it will be observed that the same order of colors is obtained by the different observers as was obtained by the writer in previous determinations, viz., red, green and blue. The following special points are of interest in connection with these tables:

1. Although the distances at which the different observers could read the test characters under daylight illumination varied considerably, their acuity values for white illumination, based on their daylight acuity, agree very closely. The reading distances for each observer with daylight illumination were as follows: Ri., 272 cm., a.d. 7 cm.; Br., 316 cm., a.d. 5 cm.; H., 310 cm., a.d. 8 cm.; Be.,

305 cm., a.d. 6 cm. The slightly higher values obtained by the writer may find a partial explanation in the fact that his determinations were made with illumination from carbon filament lamps, whereas those of the others were made with illumination from a Nernst glower, reduced in intensity by the interposition of a ground glass plate. The light from the latter source was consequently much weaker in red rays than that from the carbon filament lamps.

2. Considerable individual differences are shown with respect to the acuity with the different colors. The following table shows the relative position of the different observers, ranked roughly according to their acuity with the different colors:

	White	Red	Green	Blue
Ri.	1	2	2	1
H.	2	4	1	2
Be.	3–4	1	4	3
Br.	4–3	3	3	4

With the white and blue lights the relative positions are the same, and the individuals who hold the extremes with these colors hold mean positions with the red and green. On the other hand, H., who ranks lowest with red illumination, ranks highest with the green, and Be., who ranks highest with the red illumination, has the lowest rank with the green. These differences correspond to differences which were incidentally brought out in connection with photometric determinations of the colored lights. In determining the candle powers of the illuminations Be. secured a considerably higher value for the red than did the writer, and a somewhat lower value for the green. H., on the other hand, secured a higher value for the green than did the writer. These observations on the luminosity value of the lights were not made with sufficient accuracy to carry any great significance, but the comparison is at least suggestive.

It would seem from these observations as from others of similar character that sensitivity to the green is in an inverse relation to sensitivity to the red, a high sensitivity to red implying a low sensitivity to green, and vice versa.

TABLE XV

	Intensities in Meter-candles									
	.125	.25	.50	1.	2.	3.	4.	5.	8.	10.
White	*.29	*.36	*.44	*.50	.60	.64	.69	.71	.75	*.79
Red	*.25	*.37	*.48	.53	.59	.62	.64	.65	.69	.71
Green	.18	.23	.30	.38	.44	.48	.52	*.52	*.56	*.57
Blue	.17	.22	.27	.36	.42	.48	*.49	*.44	*.48	

Table XV. gives the *average* acuity of the four observers for different intensities of the different colors and white. In some cases this value is secured from fewer than four observers, for the reason that the observers did not all cover the total range of intensities. Such partial averages are indicated by an asterisk.

The curves plotted from these average values are shown in Fig. 9. The numeral above any point on a curve indicates the number of individual values entering into the average. In cases where the numerals are omitted, the average represents the values of all four observers.

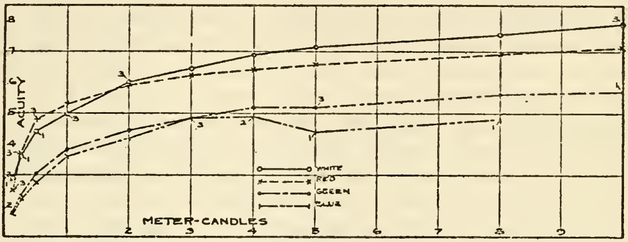


FIG. 9.

The conclusions which may be drawn from the average results of the four observers coincide with those from the preliminary observations about as closely as measurements made by one individual may be expected to coincide with an average.

Considering, first, the change in acuity as related to variations in the intensity of white light, it may be said that an acuity of one fourth is secured with an intensity of less than one eighth of a meter-candle; one half acuity with one meter-candle or less; and three fourths acuity with eight meter-candles or less of intensity. This series of observations was not run sufficiently high in intensity to attain unit acuity, although from the data secured it is obvious that a higher intensity would have been required than was required in the preliminary observations. The difference is probably to be explained by the difference in the test characters which were used.

With respect to the comparative efficiency of lights of different colors, these results make it clear that the red end of the spectrum is much more favorable to acuity than the green, the values for the red ranging from 20 to 50 per cent. above those for the green. As between red illumination and uncolored illumination, the difference appears to be very slight, although, on the whole, it is in favor of uncolored illumination. The values for blue run very close to those for green, but somewhat lower.

V

SUPPLEMENTARY OBSERVATIONS

In order to include a greater number of observers in the acuity test, the investigation, which was necessarily discontinued in June, 1910, was resumed in May, 1911. The procedure was the same as in the earlier experiments, except that a change was made in the source of the colored illumination. In the course of the work with the colored liquids it was found that these were subject to continual and irregular changes in density, due to evaporation and heating from the glower during the observations. A satisfactory substitute for the green liquid was found in the photographic color filter prepared by the Cramer Dry Plate Company, of St. Louis, Mo. This filter transmits a band in the spectrum lying between the wave-lengths of 490 and 560 $\mu\mu$.

To secure red illumination a piece of ruby glass was substituted for the poncean red solution. This yielded a pure red with approximately the same limits of wave-length as the liquid. Observations with blue illumination were discontinued, inasmuch as the work previously done indicated that so far as acuity was concerned the blue illumination might be regarded merely as a modification of the green.

In view of the fact that the general direction of the acuity curve was determined with sufficient definiteness in previous observations, it was not considered necessary in this series to use more than four variations of intensity with the colored lights, two points being located in the rapidly ascending portion of the curve, and the other two in that portion of the curve in which large increases in intensity are attended with but slight variations in acuity. For the uncolored illumination only two degrees of intensity were used, as these were sufficient to afford a satisfactory basis of comparison.

Table XVI. gives the results of these additional acuity observations for the several individuals, and Table XVII. gives the same values reduced to equal intensities, for purposes of comparison. The values given in the latter table were gotten by plotting the curves (Figs. 10, 11, 12, 13, 14) from Table XVI., and measuring the ordinates for the given abscissas, after smoothing out the curves. The figures given are, therefore, only approximate.

TABLE XVI

P.

	White		Red				Green			
Intensity .	8.46	15.42	.41	.75	3.00	18.75	.84	1.54	6.15	38.40
Acuity ...	.68	.75	.38	.45	.60	.74	.52	.55	.64	.73

H.

	White		Red				Green			
Intensity .	8.46	15.42	.39	.71	2.83	17.70	.77	1.40	5.60	35.00
Acuity ...	.65	.74	.35	.42	.57	.73	.38	.42	.57	.71

W.

	White		Red				Green			
Intensity .	7.68	13.75	.37	.68	2.75	17.10	.69	1.25	5.00	31.20
Acuity ...	.72	.75	.37	.42	.56	.67	.43	.53	.65	.83

S.

	White		Red				Green			
Intensity .	8.46	15.42	.43	.79	3.15	19.81	.84	1.53	6.11	38.19
Acuity ...	.81	.85	.51	.61	.75	.86	.41	.49	.64	.72

R.

	White		Red				Green			
Intensity .	8.46	15.42	.32	.58	2.32	14.50	.85	1.56	6.25	39.06
Acuity ...	.79	.82	.31	.42	.64	.97	.49	.54	.65	.91

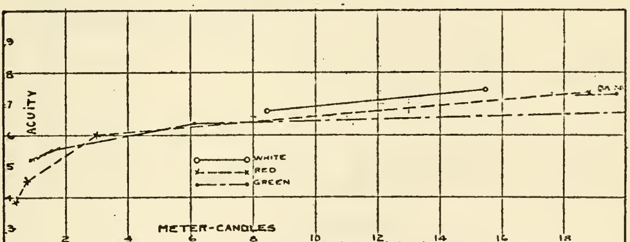


FIG 10.

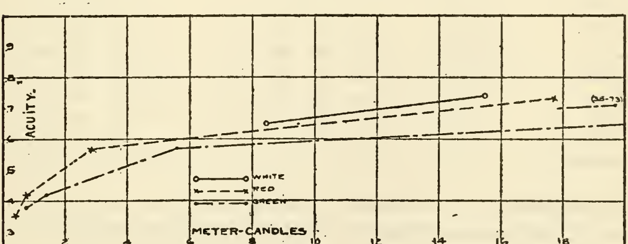


FIG 11

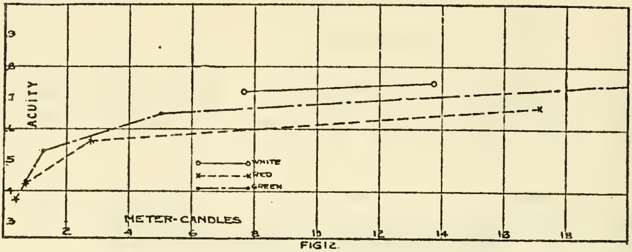


FIG 12.

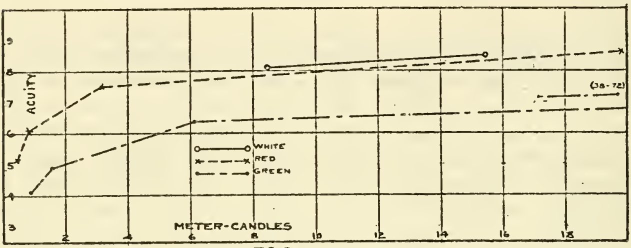


FIG 13

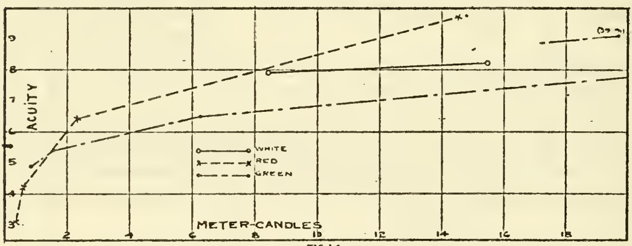


FIG 14.

TABLE XVII

	White		*Red*				*Green*			
Intensity in m-c.	9	15	1	3	9	15	1	3	9	15
Observer P.	.69	.74	.48	.60	.66	.71	.53	.60	.65	.67
Observer H.	.66	.73	.46	.58	.64	.70	.40	.50	.59	.62
Observer W.	.73	.75	.47	.57	.61	.66	.49	.62	.67	.71
Observer S.	.81	.85	.63	.75	.79	.83	.42	.57	.65	.67
Observer R.	.79	.82	.52	.68	.85	.98	.51	.60	.69	.73
Average	.73	.78	.51	.63	.71	.78	.47	.58	.65	.68

While this series of observations does not show quite so great a difference in the relative efficiency of red and green illumination as

preceding series, it is nevertheless seen that with one exception the results support the general conclusions already stated, namely that green illumination is less favorable to acuity than either red or white, and that as between red and white there is a slight difference in favor of the uncolored illumination.

Individual differences are again conspicuous and interesting. Three of the five observers get practically identical measures of acuity for white light, while showing considerable diversity in the values for red and green. One shows a decided advantage for the red, the second only a slight advantage, while the third obtains considerably higher acuity with the green. The two observers whose values for white light diverge from those of the other three agree with each other and have a noticeably higher acuity for both white and red illuminations.

One of these observers (R) stated that he feels uncomfortable in ordinary daylight illumination, and that he very much prefers to work under artificial illumination. Measurements of his pupillary reaction showed that under varying intensities of illumination the diameter of his pupil consistently exceeded that of the writer by almost fifty per cent. This observer secured practically unit acuity with less than fifteen meter-candles of illumination with the red, whereas the same degree of acuity was not reached with forty meter-candles with the green.

VI

DISCUSSION OF RESULTS

In order to emphasize the great diversity in the conclusions reached as a result of the various investigations already referred to, the following brief summary is given.

1. König and Broca and Laporte agree with Helmholtz in the view that there is no appreciable difference in acuity between illuminations of different colors, nor is there any difference between colored and colorless illumination. Failure to determine accurately the relative intensities of illumination constitutes the chief ground on which to question these conclusions.

2. Uhthoff and Örum support, in general, the conclusions of the present investigation, ascribing the highest efficiency to white illumination, with red, green and blue following in the order named.

3. Boltunow, on the other hand, while attributing the highest efficiency to white light, finds a decided advantage in acuity for green illumination, as compared with red. In criticism of his work it has already been pointed out that his test character was not well adapted to the purpose, and that the method of looking directly toward the source of illumination does not afford an accurate test of acuity. This method in reality involves the perception of brightness rather than the perception of form, a distinction which is considered elsewhere. This conclusion is in accord with the assertion of Engelmann[1] that in microscopic work green illumination yields better results than red, but in this kind of work also observations are made by means of transmitted light.

In seeking a theoretical explanation of the experimental data, one is impressed with the great diversity of the factors which enter into the problem. A few of these have already been made the subject of separate investigation, but it is clear that the relation of all to the main problem will have to be determined with much greater certainty before a satisfactory solution is forthcoming. The scope of the present work permits only an enumeration of the more important of these factors, together with, in some cases, a brief reference to the work already done in connection with them.

1. *The distinction between the form sense and the brightness sense* has already been referred to, and the failure to observe this

[1] Engelmann: cited by Boltunow, *Zeitschrift*, 1907–8, 42 (2), 359.

distinction has been suggested as a probable source of error in much of the work previously done in visual acuity. The partial independence of the form sense and the brightness sense is demonstrated by the familiar fact that the peripheral parts of the retina are unable to give impressions of form, whereas their sensitivity to light is, under certain conditions, even greater than that of the fovea.

According to the rod and cone theory of vision proposed by von Kries, the cones, which are found in greatest numbers in the fovea, are sensitive chiefly to color and form, as contrasted with luminosity, while the rods, which are predominantly the end-organs of the peripheral parts of the retina, yield only sensations of luminous intensity.[2]

In making this distinction we do not lose sight of the fact that for perception of detail we are largely dependent upon small differences of brightness, nor, on the other hand, of the fact that variations in luminosity may be perceived with strictly central fixation.

2. *The state of adaptation of the eye* has been clearly shown to affect acuity in general as well as the sensitivity of the eye to different colors. The sudden fall and subsequent increase in acuity in going from a brightly illuminated room into a comparatively dark one and Purkinje's phenomenon are familiar illustrations of this fact. It has been asserted[3] that for very low intensities green illumination yields a higher acuity than red.

3. *The sensitivity of the different parts of the retina to lights of different colors, in different states of adaptation.*—It has been shown that different parts of the retina do not show the same variations in sensitivity in changing from light to dark adaptation. Vaughan and Boltunow[4] find that in the state of light adaptation the sensitivity for red, green and blue light is by far the greatest at the fovea, and that it falls off rather quickly toward the periphery, about equally for all three colors. At 10 degrees from the fovea the sensitivity is about one fourth its central value, and at 20 degrees it is from one tenth to one twentieth its central value.

In dark adaptation, on the contrary, the peripheral parts are more sensitive to light than the fovea, and for green and blue the stimulus value increases enormously for the peripheral parts. For red, however, even after long adaptation, the sensitivity is less for the periphery than for the fovea. This fact is significant in connection with the explanation of the higher acuity for red illumination which will be proposed later.

[2] *Zeitschrift f. Psych. u. Physiol.*, 1896, **9**, 87.

[3] Dow, *Illuminating Engineer*, London, **2**, 233; Stuhr, *Ibid.*, p. 345.

[4] *Zeitschrift*, 1907–8, **42** (2), 1.

Pertz[5] has shown that at a distance of 1 degree from the fixation point the sensitivity of the retina in dark adaptation rises to almost 4 times its central value for blue light, while for red it falls to .70. At two and one half degrees the sensitivity for blue rises to 64 times the central value, and for red it falls to .55.

4. *Effect of accommodation, in near and distant vision.*—A number of observations on acuity have been made by J. S. Dow[6] which tend to show that with illumination of a given color the relative acuity is not the same for near and for distant vision. He concludes that for very near vision the blue end of the spectrum is the best, for moderate distances the central region, and for distant vision the red end. Dow's explanation involves the chromatic aberration of the eye, which will be considered in the next paragraph.

5. *The chromatic aberration of the eye.*—This defect of the eye as an optical instrument was first pointed out by Wollaston.[7] It may be strikingly demonstrated by means of a cobalt glass, or with the blue photographic filter, which transmits a narrow band of red in addition to the blue. Upon looking at a source of light of high luminosity, as an incandescent lamp, the filament is found to be bordered with red. If distant vision is used, the central part is red and the borders are blue. At intermediate distances, the red and blue colors overlap, and a single image of light purple hue is seen.

The following diagram, reproduced from Tscherning's "Physiologic Optics,"[8] illustrates the physical principle involved.

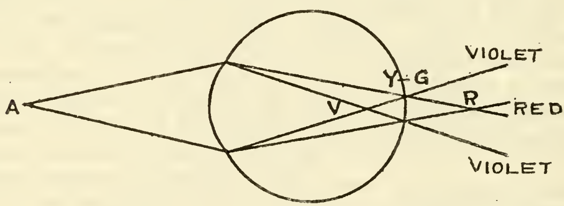


FIG 15.

Rays entering the eye from A will undergo dispersion as they

[5] *Zeitschrift*, 1897, 15, 327.
[6] *Electrical World*, 1911, 58, 955.
[7] *Philosophical Transactions*, 1801, p. 50.
[8] Tscherning's "Physiologic Optics," Philadelphia, 1900.

pass through the refractive media, the violet rays being brought to a focus in front of the retina, and the red rays behind the retina. Under ordinary illumination the intensity of the extremes of the spectrum is so low, comparatively, that vision is not noticeably impaired. It is asserted by Dr. Louis Bell[9] and others, however, that with monochromatic sources of illumination the acuity is much higher than it is with white light. In the study referred to he found that illumination from a mercury vapor arc lamp showed a value, as judged by acuity measurements, roughly from one and one half to two times its real photometric value, when compared with light of continuous spectrum derived from ordinary incandescence. Reduced to Snellen's scale, this would amount to an increase of from twenty to twenty-five per cent.

Dr. Bell found a similar result with the flaming arc lamp, which is rich in red rays, and consequently he attributes the increased acuity solely to the monochromatic character of the illumination.[10]

6. In addition to the factors above mentioned and in close connection with them the question of *individual differences* must also be taken into account. As is pointed out in the section devoted to color photometry, it has been found that every degree of sensitivity to colors is shown, ranging from the so-called normal eye, to the absolutely color-blind. König[11] states that color-blind individuals have abnormally low acuity, which he attributes to the inefficiency of the cones.

Further, the dioptric structure of the eye will have an important effect upon the acuity with different colors. In view of the chromatic aberration of the eye, it is to be expected that the far-sighted person with average color-sensitivity would secure better acuity with green or blue illumination, while red would be more favorable to the near-sighted person.

7. *The size of the pupil* as affected by illuminations of different colors may be an additional factor entering into the problem of acuity. It is of course clear that with increased aperture both chromatic and spherical aberration will be increased, resulting in reduced acuity. The increased quantity of light admitted to the eye might, on the other hand, be sufficient to offset this effect. It has, in fact, been demonstrated by Hummelsheim[12] that between the limits of 1 and 50 meter-candles of intensity acuity, as determined by the use of the Snellen charts, with a narrow pupil considerably exceeds

[9] *Electrical World,* 1911, 57, 1163.

[10] See also Luckiesch, *Electrical World,* Aug. 19, 1911.

[11] See page 11.

[12] *Arch. für Ophthalmol.,* 1898, 45 (2), 357.

acuity with a wider pupil. From 50 meter-candles upward the difference between the two is slight.

This enumeration serves to indicate the complexity of the problem. It suggests a very probable explanation of the wide variations in the conclusions reached by different observers on the basis of variations in essential details of procedure, and it emphasizes the importance of standardizing, or at least of clearly defining, the conditions of any experimental study, as to the form of test, the intensity of the illumination, the reading distance, the extent of the retinal field employed, the size of the pupil, the individual peculiarities of the observer, etc.

With respect to the present series of observations it may be said that all controllable conditions were kept as nearly as possible like those which usually obtain in the practical utilization of artificial illumination.

In support of the conclusion herein stated that light of the longer wave-lengths is more favorable to acuity than that of the shorter wave-lengths, attention is called to the following considerations.

As pointed out by König,[13] and in accordance with the theory of von Kries,[14] the rods alone are active with low intensities of illumination, whereas the cones come into play only with increased intensity. This fact must be taken in connection with the observations of Vaughan[1] and Boltunow[15] and of Pertz[16] to the effect that under dark adaptation red shows a decrease in stimulative value in passing from the fovea to the peripheral parts of the retina, while green and blue show a decided increase. On the other hand, in daylight adaptation, in which cone vision predominates, the stimulative effect of all colors decreases at equal rates in passing from the fovea. Further, red illumination shows no photochromatic interval, and in dark adaptation weak red rays produce no sensation.

All these facts indicate that the cones are comparatively more sensitive to the longer wave-lengths, while the rods are comparatively more sensitive to the green-blue end of the spectrum.

Now inasmuch as the perception of form is peculiarly the function of the cones, it follows that under red illumination at comparatively low intensities the maximum stimulation of the cones is secured, while the stimulation of the rods remains at the minimum. In consequence we have an optimum perception of form, while the

[13] See page 11.

[14] *Zeitschrift*, 1894, 9, 81.

[15] See page 36.

[16] See page 37.

sensation of brightness, which depends largely upon the stimulation of the rods, is at its minimum.

This difference in the stimulative value of red and green will be made effective in two different ways:

First, inasmuch as the brightness value of the illumination is dependent upon the sensation aroused in the rods, green illumination will have a relatively higher value than red, although this increased intensity will not be available for the cones in the perception of form.

Second, interference may be assumed to exist between the brightness sense and the form sense, so that an objectively constant stimulation of the form sense will be more or less effective, in proportion as the concurrent stimulation of the brightness sense is less or greater. Some support for this assumption of interference is found in the observed effect of a light which is brought into the peripheral part of the visual field when an object is being fixated with the fovea. Such a light always results in a reduction of acuity, even though its image may fall more than 50 degrees from the fovea.

According to the explanation here proposed, the efficiency of white light would depend upon the proportion of red or blue light which it might contain. With a high proportion or red, it might possibly equal or even surpass the efficiency of the monochromatic red. If, on the other hand, the green-blue components should predominate, its efficiency would fall below that of the red.

VII

COLOR PHOTOMETRY

Reference has already been made to the very obvious truth that in an adequate study of visual acuity the accurate determination of the intensity of illumination is a matter of the highest importance. So long as only a single color is involved, the variation of the intensity in fixed ratios in accordance with the law of inverse squares or by the use of the episkotister is a very simple matter. Or if different sources of light of the same hue are employed, their relative intensities may be determined with the more sensitive forms of photometers now in general use with an error of less than one per cent. It is possible, moreover, to make the measurements of intensity purely physical in character, if desired. The energy of the source may be determined directly by bolometric methods, or the chemical effects may be registered with minute shades of difference on the photographic plate. Quite recently the selenium cell has been proposed as affording more accurate and refined measurements of light intensity than any method hitherto used.

When, however, differences of color are involved, the problem of determining the comparative intensities of the lights becomes complicated with physiological and psychological difficulties of the most serious character.

In the studies of visual acuity already referred to, especially those of Uhthoff and König and of Broca and Laporte, these difficulties, which are generally recognized, were either entirely ignored or met in a wholly inadequate matter. König states that no attempt was made to reduce the intensities of the different colors to a common basis, and in Broca and Laporte's work the photometric measurements seem to have been made in the loosest possible way.

In the present study the complexities of color vision have been kept constantly in mind, and the determination of the comparative intensities of the lights of different colors has been regarded as the most important phase of the work. It is the purpose of this part of the report to state briefly the difficulties involved in color photometry and the various methods proposed for their solution, following this by an account of the method adopted in the present investigation, with arguments in support of the accuracy of the method.

Difficulties of a physiological character involved in estimating the comparative intensities of lights of different colors arise from the

varying sensitiveness of the eyes of different individuals to different wave-lengths, and from the varying sensitiveness of different parts of the same retina. These variations among individuals range from cases of pronounced color-blindness of well-recognized types to minor differences which are discovered only by careful comparisons. Because of these variations it is practically impossible for one observer to check up the results obtained by another, unless they happen to be so situated that the observations of both may be referred to some recognized common standard.

The existence of these individual differences in color vision was first pointed out by Professor Rood[1] in a study of his own color sensitivity as compared with that of eleven other persons. Professor Rood asserts that prior to this study "in the matter of color vision there seems to have been a tacit assumption that all persons could be divided into two classes, those with normal vision, and the color-blind. Holmgren's test with colored worsteds classifies them in this way, and analogous tests give a like result. According to this view the color vision of persons free from color-blindness has generally been considered to be alike."

In order to test this theory Professor Rood compared his own color vision with that of others, and found that while none agreed with him, they also diverged from one another. These divergences proved to be too large to permit of being attributed to errors of observation. On the basis of the results obtained, Rood found that his subjects fell naturally into two groups, equally large, with respect to their perception of green. The one group comprised those who had the highest sensitivity in the green, and the other group those who had the least sensitivity in the same color, and the highest in either the red or the blue. Inasmuch as there was no reason apparent why either group should be considered as normal rather than the other, the mean color vision of the eleven observers was taken as representing the normal, and the divergence of each person from the standard was then calculated.

At the same time tests were made of the vision of three persons who were color-blind to red; in two of the cases the defect was not previously suspected.

The following tables give the sensitivity to different colors of the various observers, the maximum sensitivity attainable in each case being represented by the number 100.

[1] *Am. Jour. Sci.*, 1899, No. 158, p. 258.

CLASS A—MINIMUM SENSITIVITY IN THE GREEN

	Red	Green	Viol.-blue
Trowbridge	100.0	91.6	95.6
Wade	97.7	97.4	100.0
Hallock	100.0	90.9	96.2
Furness	97.9	90.8	100.0
Curtis	90.5	86.6	100.0
Miss M.	100.0	81.6	99.0

CLASS B—MAXIMUM SENSITIVITY IN THE GREEN

	Red	Green	Viol. blue
White	96.1	100	95.8
Parker	85.7	100	95.8
Dennett	93.8	100	91.5
Tufts	89.9	100	87.8
Day	82.9	100	93.3

COLOR-BLIND GROUP

	Red	Green	Blue
Alsberg	30.3	88.1	100.0
Mr. W.	35.6	85.5	100.0
Mr. O.	35.3	100.0	93.9

These results clearly indicate that wide variations in the determinations of the luminosity of different colors by different individuals are to be expected from purely physiological causes, and that in consequence it is necessary to know the peculiarities of color vision of the individual observer before his results can be of any value for purposes of comparison. These errors, however, for a given individual may be regarded as practically constant, and corrections may be made for them by reference to a fixed standard, obtained, as Professor Rood suggested, by adopting the mean of a great number of observations.

Difficulties which have a psychological basis, on the other hand, give rise to discrepancies which are much more serious, and which at the same time seem incapable of elimination. They arise from the well-known fact that color sensations are not simple, but on the contrary highly complex, and that it is practically impossible in ordinary experience to analyze them into their component elements. There are involved, in the first place, all the variations in hue which are found as we pass from the red end of the spectrum to the violet. It is a matter of common observation that the colors in the lower part of the spectrum, the reds and oranges, produce an impression of greater warmth or "liveliness" than the hues of shorter wave-length, and this impression the observer is naturally disposed to interpret in terms of brightness, which constitutes a second and quite distinct quality of color sensations.

A third element of color sensation is that commonly designated as saturation, depending upon the proportion of the black-white sensation which enters into the whole complex. From a physical point of view these different qualities of color sensation are dependent, respectively, upon the absolute wave-length, the amplitude of the

vibration or the energy of the light wave, and the complexity of the wave-form. Now we know that change of wave-length brings with it variation in both brightness and saturation, and change of energy or brightness is accompanied by changes in both hue and saturation. It is therefore practically impossible even for a trained observer to eliminate the effects of hue and saturation in making judgments of brightness, the quality with which we are concerned in color photometry.

Notwithstanding this inherent difficulty, a very large proportion of investigators who have attempted to make comparisons of the intensities of lights of different colors have adopted some form of the direct method, in which the observer relies solely upon his unaided judgment. In the so-called indirect methods the effort is made either to eliminate entirely the disturbing factor of the color-tone, or at least to control it more carefully. Of the direct methods Helmholtz makes the following criticism: "I must explain that personally I put no confidence in my judgment concerning the equality in luminosity of differently colored surfaces. I admit, however, that of two differently colored fields, one can be so much darkened that there remains no doubt that the other is brighter."[2]

Helmholtz views with considerable scepticism the constant values obtained by certain observers, and says of them: "Observers who have trained themselves in the same observations attain finally a somewhat greater certainty, but this might indeed be secured as well through constant practise or greater attention to various accessory influences."[3]

Von Kries has practically the same criticism to offer concerning the direct methods, but is even less favorable to the indirect methods. Of the latter he says: "Whatever else may be said of these methods, it is at least certain that for each pair of lights found to be equally bright, some definite physiological relation exists; what this relation is, however, is not at all certain. Above all, it does not seem appropriate that one should speak of these as 'methods for the comparison of the brightness of different colored lights.' Even if the physiological relation which exists were known, yet the last argument that the method really measures the brightness must be found in the fact that the values obtained coincide with those obtained by direct comparison. The direct comparison has the last word."[4]

Space will not permit reference to the many attempts that have been made to compare the intensities of lights of different colors by

[2] "Handbuch der physiologischen Optik," 2d ed., p. 440.
[3] "Handbuch der physiologischen Optik," 2d ed., p. 428.
[4] Nagel's "Handbuch der Physiol. des Menschen," Vol. 3, p. 259.

the direct method. The general method of procedure and character of results are well exemplified in the most recent and at the same time most exhaustive study of this sort which was conducted by Dr. Herbert Sidney Langfeld in 1908 in the Psychological Institute of the University of Berlin, under the direction of Professor Carl Stumpf.[5]

Accepting the view of Von Kries as to the superiority of the direct method over the indirect, Dr. Langfeld chose the former, comparing each color successively with different shades of gray. He explains that he does not regard brightness merely as the intensity of any radiation which may be measured by physical means, but solely as a quality which attaches to color as a phenomenon. By brightness he understands a simple experience, which can not be described in other terms, and which is to be illustrated only by reference to results obtained by experiment. It must be ascribed to "tonfreie" as well as to "bunte" "Farben." In "tone-free colors," that is, the grays, the nuance varies along with the brightness from absolute white to absolute black. The variations in nuance are qualitative, those in brightness are quantitative. Therefore, whenever we determine the brightness of a color, whether it is a tone-free, a saturated or an unsaturated color, the brightness is in all cases the same property. It is not correct to say, as is often done, that the brightness is the gray contained in the color.

In his apparatus Dr. Langfeld employed the principle of Hering's "Nuancierungsapparat." The observer looked through an aperture in a gray cardboard upon a field in which could be made to appear either the colored paper whose brightness was to be determined, or a screen of gray paper whose brightness could be varied by rotating it on a horizontal axis. The fields were illuminated by a Nernst lamp of 150 candle power, whose rays were passed through a blue glass in order to weaken the yellow components.

In discussing his results, Dr. Langfeld says that he found that his judgments of brightness, as was true also in the cases of the other observers, might be of two distinct kinds. He says: "Either I could compare the colors, by attending to the light which seemed to come from them, in which process I abstracted from the color-tone, which remained in the background of consciousness, or I could devote my attention to the colors as such. . . . In each case I had an impression of brightness, but each impression was quite distinct." He quotes numerous expressions from his observers which indicate that they experienced the same difficulties throughout the series of observa-

[5] *Zeitschrift f. Psychol.*, 1909, 53, 113–178.

tions. Some of them recognized the distinction between the two classes of judgments. Others only felt the disconcerting effects without understanding their cause.

It is on the basis of this distinction that Langfeld explains the great scattering of his values, as well as of the values obtained by the others. With certain colors the impression of the color-tone would predominate, with others the impression of the brightness as such. Thus in the blue and the yellow the values are much scattered, but they concentrate about two points, the blue at 32 and 52 (the numbers indicate the degrees of rotation of the gray cardboard to match the given color in brightness), and the yellow at 57 and 80. At one time the one attitude predominated, at another time the other. In the violet only one standard of judgment was used, and in other colors both impressions combined in such a way that the values were spread out over a wide range, with no concentration at particular points.

The accompanying excerpts from the tables of results obtained will indicate the wide variations in the values. The upper line of figures for each observer gives the limits of the angles in degrees, and the second line gives the actual brightness values, in terms of the cosines of the angles.

Obs.	Red	Orange	Yellow	Green	Green-blue	Blue	Violet
L.	40–76	39–80	54–85	44–81	30–53	30–54	27–35
	(76–24)	(76–17)	(58–9)	(72–15)	(87–60)	(87–58)	(89–82)
G.	40–86	54–75	56–74	57–80	46–84	31–62	27–45
	(76–7)	(58–25)	(57–27)	(54–18)	(69–10)	(86–47)	(89–70)

Dr. Langfeld states that the most important fact to be learned from the tables is that in general two very different sets of figures are obtained from the two different standards of judgment. "Under ordinary conditions such as obtained in the researches conducted by other investigators, consistency and certainty could not be secured, except when the observers by chance adopted the same 'attitude.' But it can not be assumed from this fact that heterochromatic brightness comparison is impossible. We must maintain, on the strength of our experiments, that such comparison is possible, and that satisfactory results may be obtained if observers adopt a definite 'attitude,' and train themselves to hold to this consistently."

In a subsequent attempt to compare the brightness of spectral colors with Helmholtz's color mixing apparatus, Langfeld found that when he made the comparison on the basis of the color-tone, red was brighter than orange, and both were brighter than yellow. When the other basis of judgment was used, these three colors followed the natural order of brightness, red, orange, yellow.

However hopeful Dr. Langfeld may be as to the possibility of making these comparisons by direct methods, his results seem to be of value only in demonstrating the uncertainties that are necessarily associated with this method, and in explaining the cause of these uncertainties. Physicists meet with the same sort of difficulties in attempting to make comparisons of differently colored lights with photometers of the direct comparison type.

It was with the purpose of avoiding, if possible, these subjective difficulties that the principle of the flicker photometer was adopted in the present investigation, in preference to the direct comparison photometers in common use. This principle, however, has not as yet received much favor at the hands of physicists, and it is necessary therefore to enter at some length into the discussion of the principles involved and the results obtained which would seem to justify its use.[6]

The flicker method of photometry was first suggested by Professor Rood in a paper published in the *American Journal of Science* in September, 1893. Apparatus for the application of the principle was constantly improved and tested by Professor Rood until 1899, when he stated as the conclusion of his investigations that "the accuracy attainable with the flicker photometer, as at present constructed and using lights of different colors almost spectral in hue,

[6] Since this chapter on photometry was written there has come to be more general agreement among physicists as to the trustworthiness of the flicker method in heterochromatic photometry. The following quotations represent the view held by many investigators at the present time.

Dr. Louis Bell says: "I am strongly of the opinion that one makes no mistake in assuming the substantial correctness of the flicker method where heterochromatic comparisons are to be made—that is, if in a heterochromatic comparison there is a substantial difference between the results obtained with the flicker instrument and with an equality-of-brightness photometer, it is altogether probable that it is the latter which is in error." (*Electrical World*, 1911, 58, 637.)

Mr. Herbert E. Ives, of the laboratories of the National Electric Lamp Association, who recently made a careful study of the flicker and equality-of-brightness methods of photometry, found that "the flicker method is for all parts of the spectrum several times as sensitive as the equality-of-brightness method," and that inexperienced observers with the flicker photometer are able to make determinations which agree very closely with those of experienced observers, whereas with the direct comparison methods their variations may be from five to ten times as great. He states as his conclusion that "the much greater sensibility and ease of setting of the flicker method point to its decided superiority for heterochromatic photometry." (*Transactions of the Illuminating Engineering Society*, 1910, 5, 711.)

is about the same as with ordinary photometers using plain white light, or light of exactly the same color."[7]

Following the work of Rood the principle of the flicker was further tested out by Professor Frank P. Whitman,[8] using colored papers of the Milton Bradley series and colored glasses. The precision of setting possible with the apparatus was first tested by making over 100 observations with nineteen different colors, covering the whole range of the spectrum. The difference between two successive readings was seldom more than one per cent., although in a few cases it ran as much as two or three per cent.

The second test was concerned with the comparative values obtained by different observers. Two lamps were balanced against each other by ordinary photometric methods at respective distances from the photometer head of 2.98 feet and 3.02 feet. The same values were obtained by each observer. By the flicker method the distances were 2.96 and 3.04 feet for one observer, and 2.98 and 3.02 for the other. A red glass was then interposed on one side and a green glass on the other. The readings than became as follows:

	Direct	Flicker
Observer 1	2.59–3.41	3.79–2.21
Observer 2	3.08–2.92	3.88–2.12

These results show, first, that when lights of exactly the same color are compared and brightness only is involved, two observers who get indentical values by direct methods will get practically identical results by the flicker method; and, second, that where color differences are involved, the values of different observers by the direct method may vary widely, in this case by almost 20 per cent., whereas by the flicker method the difference is very slight, in this case only a little over 2 per cent.

A third series of experiments made by Whitman demonstrated the fact that the values obtained with bright and with faint illuminations did not appreciably differ, and that thus the difficulties associated with Purkinje's phenomenon and met with in direct comparisons are avoided with the flicker method.

The most important point established by Whitman was that the flicker method gives a true measure of luminosity comparable with that obtained in other trustworthy ways. The luminosity values of differently colored papers were determined by means of the flicker photometer and by the use of the Maxwell discs, with the following results:

[7] *Amer. Jour. Sci.*, 1899, No. 158, p. 194.

[8] *Physical Review*, 1896, 3, 241.

	Red	Green	Blue	White
Color equation—Maxwell discs ...	40.5	49.2	10.3	22.6
Luminosity, by flicker	.238	.295	.106	
Luminosity value	9.64	14.50	1.09	
Total luminosity of colors				25.23

	Red	Green-yellow	Blue	White
Color equation—Maxwell discs ...	18.5	34.0	47.5	30.4
Luminosity, by flicker	.238	.617	.106	
Luminosity value	4.41	20.96	5.03	
Total luminosity of colors				30.4

The upper line of numbers in each table represents the percentage of the whole disc occupied by the given color, the combination of the three colors being matched against the white-black of the central part. "The amount of white light in the black-white combination, corrected for the light reflected by the black portion, is the measure of the luminosity of the colored discs in terms of white, which quantity, again, is dependent upon the luminosities of the three colors of which it is composed.

"If now the fraction of the whole circle occupied by any color is multiplied by its luminosity as measured with the flicker photometer, the result will be the amount of white equivalent to that colored sector, and the sum of the results obtained by treating each of the colored sectors in this way should equal the amount of white in the black-white disc." "Fourteen such trials were made with different colors, the results differing by one to three per cent. from exact equality."

More recently Professor Tufts,[9] of Columbia University, applied the principle of the flicker photometer to the determination of the relative luminosities of the different parts of the spectrum, and demonstrated that the sum of the luminosities of the spectrum colors determined in this way is equal to the measured luminosity of the original white to within about 3 per cent., which is well within the error of spectrophotometric measurements.

In the course of the same experiments Professor Tufts demonstrated the fact that the luminosity sense of the eye is practically independent of the color sense. He first determined his own wave-length luminosity curves for both eyes, and found them to be practically identical. He next exposed his right eye to light of a given color until it was fatigued to such an extent that all white objects viewed with that eye appeared of a complementary color. He then measured the luminosity of the given spectrum color with the fatigued

[9] *Physical Review*, 1907, 25, No. 6.

eye, and immediately after with the unfatigued eye. This was done for seven different positions in the spectrum. With one exception, that of prolonged exposure to red, the fatiguing of the eye by any color did not produce any change in the luminosity sense. Two other observers with normal color vision made the same observations and obtained similar results.

This observed independence of the luminosity sense and the color sense harmonizes well with von Kries' theory[10] that the cones are a color-perceiving apparatus, while the rods are insensitive to color, and give only sensations of luminosity. This distinction is also strikingly brought out by certain interesting experiments of Lummer.[11] By throwing a spectrum on a white screen, starting with low illumination and gradually increasing its intensity, he has shown that the first recognizable light is colorless, with the apparent maximum intensity in the blue-green. As the illumination is increased, sensations of color arise, and the point of maximum luminosity gradually shifts toward the yellow-green region, showing that the rods are most sensitive to the blue-green end of the spectrum, although they are unable to produce sensations of color as such. Lummer also shows that if a platinum filament is heated to a dull reddish luminosity and is observed directly, it appears red and sharply defined, but if observed obliquely, it appears brighter, loses its color and at the same time loses sharpness of contour.

The greater constancy of the flicker method of photometry as compared with direct comparison methods is clearly brought out in a comparative test recently made by L. W. Wild,[12] an English physicist, who has devoted considerable attention to the problem of heterochromatic photometry. He introduces his discussion with the general statement, confirmed by his experience, that "the great merit of the flicker type is that the same reading within about one per cent. can be obtained again and again, even though the lights differ in color to a considerable extent, whereas with photometers of the equality of brightness type under the same conditions of color differences the readings may lie 10 per cent. or more on either side of the mean, and consequently a very large number of readings must be taken in order to secure a true average."

In his tests Wild used a carbon filament lamp and one with a tungsten filament. Six different photometer heads were employed three based on the flicker principle, and three on the equality of brightness principle. The following table gives the maximum, the

[10] *Zeitschrift f. Psych. u. Phys., d. Sin.*, 1894, 9, 81–123.

[11] *Report of Smithsonian Institution*, 1904, 1, 249.

[12] *The Electrician*, 1909, No. 63, p. 540.

inimum and the mean scale readings. Ten readings were taken ith each flicker head, 20 with the Bunsen, and 50 with the Lummer-rodhun.

	Flickers			Contrast	Equality	
	Wild	Whitman	Simmance	Bunsen	Prism	Lummer
Maximum	1.73	1.735	1.735	1.86	2.05	2.00
Minimum	1.72	1.715	1.71	1.79	1.72	1.70
Mean	1.725	1.722	1.722	1.825	1.85	1.83

As will be seen from the table, all three photometers of the cker type give exactly the same mean values, and the range be-reen the maximum and the minimum for each instrument is very nall. On the other hand the three direct comparison photometers ot only show wide variations between the maximum and the mini-um readings in each case, but their agreement with one another in le mean readings is not nearly so close.

The conclusion drawn by Mr. Wild from the results of this study lustrates the common tendency among physicists to favor the direct mparison type of photometer as against the flicker type, even iough the latter invariably yields the more consistent results when mparative tests are made. In this case the flicker instruments .ve the tested tungsten lamp a value about 6 per cent. less than iat given by the other type, and for this reason the author concludes iat "in spite of the greater sensitiveness of the flicker photometer, will have to be discarded in favor of the Bunsen disc."

In order to test more fully the reliability of the flicker method in olor photometry, the writer made an exhaustive series of observa-ons with colored papers of the Hering series, using the photometer ead as originally designed by Professor Rood and improved by rofessor Tufts. The apparatus was further modified by the writer meet the requirements of this particular test.

The principle on which the use of the flicker photometer is based ay be briefly stated as follows: When the same point on the retina alternately stimulated by light coming from two unequally illu-inated and differently colored surfaces, a sensation of flicker esults, which is due to differences in both intensity of illumination nd color. By increasing the speed of alternation a point is reached t which the flicker resulting from the color difference disappears ecause of optical fusion. The intensity flicker, however, persists to much higher frequency of alternation, unless the two illumina-ons are equalized. The speed of alternation at which the color icker disappears varies with the intensity of illumination, but under ny conditions the color flicker disappears before the intensity icker.

Assuming the correctness of this formulation of the principle of flicker, a satisfactory means is thus afforded of eliminating the influence of color in making comparisons of intensity, an influence which, as has already been pointed out, is always noticeably present when such comparisons are attempted by direct methods.

Description of Apparatus

The essential parts of the photometer (Fig. 16) are contained in a cubical box, approximately 8 inches on a side. This box is mounted on an ordinary photometrical bench, which is conveniently graduated. Light from the two sources under comparison enters the box on either side through apertures 2 inches in diameter, and falls upon two vertical planes which are inclined to each other at a fixed angle of 90 degrees. The two planes are permanently fastened together in the form of a wedge, with the edge directed to the front of the photometer.

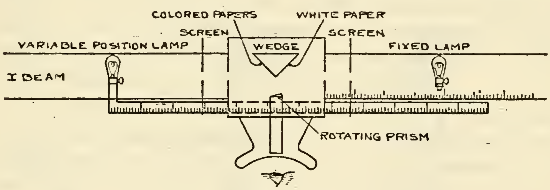


FIG 16.

Both faces of the wedge contain slots for holding small sheets of paper, either pure white or colored. By allowing the edge of the paper on one side to project slightly beyond the exact edge of the wedge, the margin of the paper on the other side is concealed, thus forming a very keen line of division between the two planes.

When the photometer head is to be used in the ordinary way, that is, to measure the relative intensity of two lights of the same color, sheets of white paper cut from the same piece are inserted in either side of the wedge. With this arrangement also lights of different colors may be compared.

In this series of observations, however, differences in color were secured not by varying the sources of light themselves, but by substituting papers of different colors for the white sheets on the faces of the wedge.

The wedge is viewed from the front through a brass tube about 9 inches long and .75 inch in diameter. The axis of this tube lies along the line which bisects the angle formed by the two planes of the wedge. At the outer end of the tube and at certain points along its length are inserted diaphragms by means of which the diameter is stopped down to about .25 inch, thus preventing reflection from the inner surface of the tube.

The inner end of this tube is about 3 inches away from the edge of the wedge, and carries a small 10-degree prism by means of which the rays of light coming from the wedge are refracted on their way to the eye. The portion of the tube which contains the prism is capable of rotation, and in consequence of this rotation the two planes of the wedge occupy the field of vision alternately in varying proportions from totality to zero. The line of division between the two planes is seen to move across the field from right to left and vice versa.

Figure 17 indicates the path of the rays of light from the wedge to the eye at different phases of the rotation of the prism, and the corresponding appearance of the field.

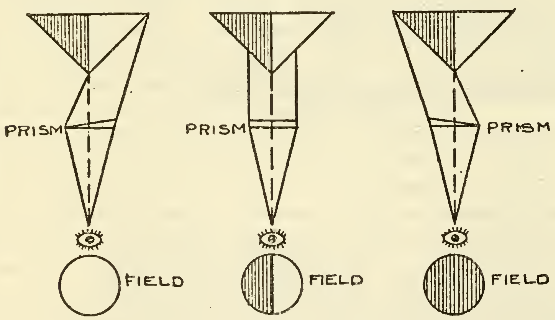


FIG. 17.

The rotation of the prism is accomplished by means of an electric motor, the speed of which may be varied within desired limits.

The eye of the observer is protected from extraneous light by a hood which is capable of being moved from side to side so that either eye may be used in the observations.

The sources of light used in this series of experiments were two carbon-filament incandescent lamps of nominally 16 candle power,

placed on the same circuit, their voltages being capable of independent variation. No effort was made to avoid momentary fluctuations in the voltage of the circuit during the observations, as both lamps were equally affected by them, and fixed values of illumination were not required.

Photometric Observations

The method of procedure was as follows: white papers were first placed upon both faces of the wedge, and the lamp to the right, which was to remain fixed, was placed at a determined distance from the photometer head, say 150 cm. The variable-position lamp was then placed at the same distance and the prism was set in rotation, the proper speed being determined by observation. If a flicker appeared with this setting, the variable-position lamp was moved further away or nearer until the flicker disappeared entirely, or was reduced to a minimum. A graduated rod running from the movable lamp under and past the center of the wedge carried a strip of white paper. In this paper a punch mark was made when the proper setting was obtained, and this procedure was repeated nine times. The mean of the ten readings was taken as the correct distance of the variable-position lamp to balance the fixed lamp.

By putting a standard lamp on the variable-position side and comparing its balancing distance with that of the first lamp used, the candle power of the latter could readily be determined. In this series the desire was not to determine the candle power of the lamp, but to so adjust the intensities of the two lamps that a photometric balance would be secured with the lamps at equal distances from the photometer head. This adjustment was secured by varying the voltage of one of the lamps. Comparisons were made also at 100 cm. and at 75 cm., until it was absolutely certain that the two lamps gave equal intensities of illumination at the same distance.

Having secured in this way a satisfactory balance of the lamps, a sheet of red paper was substituted for the white on the left side of the wedge, the fixed lamp was again set at 150 cm., and the variable-position lamp was moved backward and forward until the flicker was eliminated. As before, the mean of ten observations was taken. This procedure was repeated for distances of 100 cm. and 75 cm. In this way ten colors chosen from the Hering standard series were compared with white and their brightness values were determined in terms of the latter.

The following table (XVIII.) shows the distances at which the variable-position lamp was set with the different colors in order to balance the white when illuminated with the fixed lamp at distances of 150 cm., 100 cm., and 75 cm.

TABLE XVIII

Colors	*Fixed Lamp at 150 Cm.* Bal'g Dist.	A. D. in Per Cent.	*Fixed Lamp at 100 Cm.* Bal'g Dist.	A. D. in Per Cent.	*Fixed Lamp at 75 Cm.* Bal'g Dist.	A. D. in Per Cent.
White	150.0		100.0		75.0	
Hering red	88.6	.56	58.5	.43	43.7	.68
Brick red	79.8	.46	53.3	.47	39.6	.80
Orange	114.2	.44	75.8	.65	56.7	.66
Orange-yellow ..	139.5	.54	93.7		69.8	.36
Yellow	145.3	.51	96.7	.38	72.5	.34
Green	88.5	.56	58.7	.88	44.0	.57
Blue-green	70.5	.71	46.5	.81	35.0	.72
Blue	60.2	.41	40.0	.31	29.9	.42
Indigo	52.4	.96	34.8	1.08	25.8	1.45
Violet	53.0	.47	35.1	.72	26.1	.48

Inasmuch as the consistency of the observations with one another affords the most available means of judging of the accuracy of the observations, it is of interest to note that in only two cases do the average deviations exceed one per cent., and that the average of all the average deviations is only a little over one half of one per cent.

The following table (XIX.) shows the comparative brightness values of the different colors as determined at different distances, on the basis of a value of 100 assigned to the white. The values of the colors are, of course, proportional to the squares of the distances of the lamps which illuminate them.

TABLE XIX

Colors	*Fixed Lamp at* 150 Cm.	100 Cm.	75 Cm.	Average	A. D. in Per Cent.
White	100.0	100.0	100.0	100.0	
Hering red	34.8	34.2	33.9	34.3	.9
Brick red	28.3	28.4	27.9	28.2	.7
Orange	57.9	57.4	57.2	57.5	.4
Orange-yellow ...	86.4	87.8	86.6	86.9	.7
Yellow	93.8	93.5	93.4	93.6	.2
Green	34.8	34.4	34.4	34.5	.5
Blue-green	22.1	21.6	21.8	21.8	.8
Blue	16.1	16.0	15.9	16.0	.4
Indigo	12.0	12.1	11.8	12.0	.8
Violet	12.5	12.3	12.1	12.3	1.1

These results indicate that wide variations in the intensity of illumination do not produce noticeable changes in the comparative brightness values of the colored papers. The illumination at 75 cm. was four times as great as that at 150 cm., but notwithstanding this fact the deviations from the average values are less than one per cent. This is in striking contrast with results obtained from direct comparisons, in which, as has already been pointed out, the deviations run as high as 10 per cent. (p. 50).

In addition to comparing each of the colors separately with white, the conditions were made still more rigid by balancing the various colors against each other directly. For example, the red paper was placed on the right side of the wedge, and its lamp was set at the distance required by the red to balance the white at 100 cm. —viz., 88.6 cm. The other colors and the red itself were then inserted successively on the left face of the wedge. If the method were strictly accurate, each color should have its lamp at the same distance as when that color was balanced against the white at 100 cm.

Table XX. gives the distances for the various colors on the right side when balanced against red, green and violet placed successively on the left side.

TABLE XX

	Against Red at 88.6 Cm.		*Against Green at 88.5 Cm.*		*Against Violet at 53 Cm.*	
	Dist.	A. D. in Per Cent.	Dist.	A. D. in Per Cent.	Dist.	A. D. in Per Cent.
Hering red ...	89.0	.14			89.0	.42
Orange	115.5	.44	115.0	.32	115.2	.54
Yellow	146.3	.41	145.3	.34	145.2	.34
Green	89.1	.70	89.1	.70	88.2	.56
Blue-green ...					70.9	.70
Blue	61.4	.61	61.5	.81	60.8	1.23
Indigo	52.9				52.9	.48
Violet					52.4	.48

It will be observed that green when balanced against red shows no higher percentage of average deviation in the readings than when it is balanced against itself. In each case the average deviation, which measures the variability of the series of observations, is .7 per cent. This means that with this form of photometer differences in color of the fields compared, even when the difference is as great as that which exists between complementary colors, as red and green, produce no appreciable influence in the results.

Table XXI. gives the brightness values of the colors in this series of observations reduced to the same basis as in Table XIX. The values as determined in Table XIX. are reproduced for purposes of comparison.

TABLE XXI

	Balanced Against			
	Red	Green	Violet	White (Table XIX.)
Hering red	35.2		35.2	34.3
Orange	59.3	58.8	59.0	57.5
Yellow	95.1	93.8	93.8	93.6
Green	35.3	35.3	35.7	34.5
Blue-green			22.3	21.8
Blue	16.7	16.8	16.4	16.0
Indigo	12.4		12.4	12.0
Violet			12.2	12.3

The fact that practically all the values as determined in this series run slightly higher than those obtained in the original series would raise the suspicion that in spite of the precautions taken the photometer was not absolutely in balance. It was found, for example, in subsequent tests of the apparatus that it was so sensitive that a variation of more than one per cent. might be caused by having the grain of the paper used on the face of the wedge run in the wrong direction.

The belief in the accuracy of the flicker method in determining the brightness value of lights of different colors receives further confirmation in the work of Polimanti.[1] He studied the distribution of intensity in the spectrum by means of the flicker method and also by peripheral vision, and found that the distribution of the flicker values coincides approximately with the peripherally determined values, and that both are one and the same function of the wavelength.

[13] *Zeitschrift f. Physiologie der Sinnesorgane,* 1889, **19**, 263.

VIII

CONCLUSION

In summarizing the results of this study, attention is directed to the following points:

1. As regards the relation of acuity to intensity, it is shown that with uncolored illumination approximately 75 per cent. of daylight acuity is attained with an intensity of from 8 to 10 meter-candles; with a reduction of intensity below this point the acuity decreases rapidly, and with an increase of intensity beyond this point the acuity rises very slowly, unit acuity being attained with an intensity of from 40 to 50 meter-candles

As in daylight vision, after unit acuity is attained, further increase of intensity shows practically no gain in acuity. It may therefore be considered that intensities of 8 and 40 meter-candles constitute approximately the lower and upper limits, respectively, of suitable illumination for ordinary purposes.

2. As to the relative efficiency of red and green or blue illumination, the advantage lies decidedly with the red. Monochromatic yellow does not enter into this comparison. So-called white illumination gives a slightly higher acuity than red, but inasmuch as white illumination is predominantly yellow, it is quite possible that monochromatic yellow would have the same influence on acuity as white.

3. A probable explanation of the greater efficiency of red illumination is to be found in the apparently greater sensitivity of the form perceiving end-organs, the cones, to light of longer wave-length, as compared with the brightness perceiving elements, the rods, which have been shown to be more sensitive to the shorter wave-lengths.

4. In the study of visual acuity many distinct factors are involved, failure to regard any of which will seriously affect the results obtained. Among these the most important are:

(*a*) *Photometric determinations.*—Accurate estimation of relative intensities of colored illumination by direct methods is exceedingly difficult, if not impossible, and the flicker method is proposed as the only satisfactory one for making heterochromatic comparisons;

(*b*) *Test-characters.*—Care should be taken that the test-character employed actually measures the form sense rather than the brightness sense, and that it involves the use of the eye under condi-

tions approximately similar to those under which the latter is commonly used;

(*c*) *Individual differences.*—The demonstrated existence of great individual variations makes it imperative that the visual peculiarities of any observer be definitely determined. Value can attach only to results which represent the average of a number of observers.